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December 2016.

THE NZEB RETROFIT OF REGIONAL TECHNICAL COLLEGE BUILDINGS

CONTENTS VOLUME1

DECLARATION

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The thesis submitted is the candidate's own work and has not been submitted for another degree, either at University College Cork or elsewhere.

Marc Ó'Riain

Abstract

The EU introduced nearly Zero Energy Building (nZEB) performance targets for all new and retrofit public buildings by 2019 and all commercial buildings by 2021 (EPBD 2010). In Ireland, a low regulatory scenario persists for non-residential retrofits since 1974. McKinsey (2009) established retrofit as one of the most cost effective means of achieving emission abatement. With over 50% of Ireland's commercial building stock pre-dating energy regulation (1919-1992), this paper establishes that it is possible to retrofit precast concrete building typologies from the 1960s/70s, using primarily passive means (thus reinvesting structural embodied energy, diverting waste from landfill) and reducing regulated operational energy demand by up to 74%, achieving Net Zero Energy Building performance. However systemic barriers established by Steinmuller (2008) to NZEB adoption are retarding the potential for Ireland to meet the aspirations of the Energy Performance Directive (2010). This paper explores the barriers that retard NZEB retrofit adoption in an Irish legislative context, and proposes a systematic design process to address performance oriented building retrofits.

A dialectical stance adopting a mixed method research approach, includes case study analysis, a participatory action research study of the processes leading to Ireland's first NZEB retrofit and qualitative content/frequency analysis of standard and deviant cases at Cork Institute of Technology, capturing both internal design process issues and a multiplicity of systemic parameters that contribute to the barriers that retard the widespread market adoption of measurable Net Zero Energy Buildings (NZEB) in Ireland.

Outside the design process the structural pillars of low mandatory minimum standards and a poor availability of financing models undermine the development of the low energy-building sector in Ireland. Without this external framework, market forces result in lower performance targets at the outset of projects, truncating design processes, impacting decision-making and reducing opportunities for the adoption of energy conservation measures. Case study analysis illustrates that design practices in Ireland may suffer from a low usage of energy auditing, economic scenario analysis, performance assessments, risk assessment, building performance simulation modelling, performance measurement/validation and post occupancy evaluation due principally to cost, time, software, education and training issues. A poor standard of knowledge, experience, and understanding of performance oriented design practices impacts the development of relevant skill sets, tacit knowledge and suitable design processes to deliver on the aspirations of the Energy Performance in Buildings Directive 2010 in an Irish context. To address this issue there are opportunities to augment the existing design processes with specialist skillsets, developing new practices and broadening the experience of existing practice with perfomance oriented design processes.

ACRONYMS

Acronym	Expansion
AA	ARUP Associates
AC	Air conditioning
ASHP	Air Source Heat pump
ACD	Acceptable construction details
BDA	Building Design Associates
BEPS	Building Energy Performance Standards (US)
BER	Building Energy Rating
BMS	Building Management System
BPS	Building performance simulation
CIT	Cork Institute of Technology
CLASP	Consortium of Local Authority Schools Programmes
CoCoNuke	Coal, conservation and nuclear policy (UK)
DoECLG	Department of Environment, Community and Local Government
DEAP	Domestic Energy Assessment Procedure
DEC	Display Energy Certificates
DKIT	Dundalk Institute of Technology
DTI	Department of Trade and Industry (UK)
EE1	Fabric Package Energy Emissions 1
EPB 2002	Energy in buildings Directive 2002 (EU)
ECON guides	UK ENERGY CONSUMPTION GUIDE
EPBD	Energy Performance in Buildings Directive
EC	European Community Area
EPA	Environmental Protection Agency
EPC	Energy Performance Coefficient
ETSU	Energy Technology Support Unit (UK)
ESCOs	Energy Service Companies
EU	European Union
GHG	Green House Gas
GNP	Gross national Product
HUD-MPS 74	US Housing Minimum Property Standards 1974
IAQ	Indoor air quality
IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
IEA	International energy Agency
IES	Integrated Engineering Software
IoT	Institutes of Technology
ISBEM	Simplified Building Energy Model
LPHW	Low Pressure Hot Water heating system

MS	Member State
M&M	Materials and Metallurgy
MVHR	Mechanical ventilation heat recovery
MPEPC	Maximum permitted energy performance coefficient
NEAP	Non-domestic Energy Assessment Procedure
NPI	Normalised Performance Indicator
NPV	Net Present Value
nZEB	Nearly Zero Energy Building
NZEB	Net Zero Energy Building
NV	Natural Ventilation
OHL	Overall heat loss method (Ireland)
OPEC	Organization Of Petroleum Exporting Countries
OAPEC	Organization of Arab Petroleum Exporting Countries
Pa	Pascals
PAR	Participatory Action Research
PhPP	Passive House Planning package
PCP	Product, context and process analysis
Part L	Irish Energy Conservation in Building regulations
PE	Primary Energy
PV	Photovoltaic
RIAI	Royal Institute of Architects in Ireland
ROI	Return on investment
RTA	Radiant thermal asymmetry
SAR	Second assessment report (IPCC)
SEAI	Sustainable Energy Authority of Ireland
Therm 5	Thermal Bridging Simulation Software
TC	Thermal comfort
TGD	Technical Guidance Document
Trynsys	Transient System Simulation Tool
WuFi	Transient Heat and Moisture Transport software
WW2	World War 2
Zero2020	NZEB pilot project in Cork.

Acknowledgements

Thanks to: Primary Supervisor: Professor Kevin McCartney

Special thanks to:

Secondary Supervisor: Dr. Jim Harrison,

Dr. Adam De Eyto for all his direction and advice,

My wide Deborah Ni Riain for all the help and support,

Fergus Delaney and Paul Ó Sullivan, for all the collaboration and help,

CIT for allowing us to test out our ideas,

All those who allowed this researcher to interview them, and were so willing to contribute their time, documents and data, especially from the Institutes of Technology, the Department of Education, World Bank and Houses of the Oireactas library.

Dedicated to my daughter Abililina Ni Riain, for all the time I've missed, I'll make it up!

RESEARCHERS NOTES

I entered this research process after 15 years of architectural and interiors practice, involving the adaption of existing buildings. In practice, I found a low level of client demand, or priority for sustainable design solutions. Clients appeared to separate capital investment budgets and the operation costs, even when they were the occupants. In practice, client budgets were often set at a very early stage, sometimes prior to the design team appointment, based on national market average capital expenditures, which are published annually in Quantity Surveyors reports. Reflecting on my own practice, I questioned my process, communications, strategy and abilities to deliver more sustainable design solutions, in this context. It was for this reason I set about this research process.

Educated primarily as a designer, my response to most challenges is to understand the systemic inputs any given challenge and ask why a certain approach might be taken or a certain solution might be sought. The design process often asks the designer to question the problem from first principles rather than from the last instantiation. Systems design, for me, was a good methodological process for challenging existing wisdom and existing strategies, where these had not delivered sufficient solutions. This approach very much influenced how I addressed and approached the research. I initially questioned 'sustainability' and how the client or investor could value it in the construction of or operation of a building. Energy was an obvious factor, which influenced carbon emissions through its consumption, and drove additional costs where the design solution was inefficient. At an early stage of the research the focus shifted away from sustainable building retrofit towards low energy building retrofit as a measurable criterion with both internal and external costs.

Having looked at a number of building typologies nearing their refurbishment cycles, I chose to examine the RTC building typologies due to their scale, construction type, access, the availability of some original data, and their continued ownership from their original construction date. Unfortunately, there was little or nothing written about them, so there was a large vacuum of secondary data, driving an intense primary data research period. I first set about establishing how and why the RTCs were designed and built, trying to understand the motivations of the designers, clients and investors. I also then examined the external factors that may have influenced their design, such as political, social and economic contexts.

In a meeting in late 2010 was invited to collaborate on retrofit project with a number of fellow lecturers, engineers and a client, to renovate part of the original RTC building in Cork, as a research facility and living lab. The sudden dawning of the retrofit project presented an opportunity, which was far too good to turn down, as it mirrored my research topic and area of interest. It appealed to me because it presented an opportunity to apply research theories in practice and build upon 15 years of knowledge in building renovation.

The project also afforded me the opportunity to work with other disciplines, as was the case in practice, to carry out a low energy retrofit test bed. Quite quickly the dynamic in the meeting shifted the existing design solution away from a very active based strategy, towards a passive based strategy, strongly influenced by the recently published Energy Performance in Buildings Directive (May 2010). Whilst the initial meeting had a large number of people involved, the project (which was then referred to as PRD74), continued to develop with the client, a building services researcher, a mechanical engineering researcher and myself, the architectural researcher. The potential of project funding for a tested pilot project allowed the team to develop a strategy for low energy performance and appoint a design team. As for me, it provided a fast learning curve, driving me to explore Passive House strategies and building simulation tools, as I realised the shortfall in my own skills, compared to that of the engineers. The project offered a great insight and reflection on practice. Whilst the engineering researchers were focused on the details of air movement, ventilation, and active systems efficiency, I was far more interested in the general principles of energy conservation through fabric super-insulation and strategic energy demand reductions. It was critical to me that the design solution be viable and scalable beyond this instantiation. Therefore the blend of research focuses amongst the research team was very symbiotic, making for a very constructive and dynamic team.

The project became known as the Zero2020 project. It addressed a number of the questions that arise in the introduction chapter and raises more questions that I would not have initially considered. The outcome of the Pilot Project perhaps only addressed that particular instantiation, establishing the viability or potential of an existing building to achieve a very low energy performance through retrofit. However, the systemic question of market demand then arose. What would prevent a client from aspiring to a low energy building retrofit, at the outset? What were the barriers to the greater adoption of design solutions that could reduce green house gas emissions and result in operational cost savings for the client? It was this question that prompted the systemic study of legislation and geo-political economics. Looking back on it now, the research had started as a reflection on my own practice/design process, and ended up becoming a reflection on the systemic inputs influencing low energy building retrofit, with significant implications for national legislation, therefore having a far wider impact than initially considered.

The research you are about to read is necessarily broad in nature, examining the various inputs and factors that influence both building design and building retrofit. It is less focussed on the micro details of envelope performance (although this in indeed is addressed) and more about the barriers to scalability of low energy building retrofit design solutions.

Marc Ó'Riain

CHAPTER 1

AN INTRODUCTION TO THE NZEB RETROFIT OF REGIONAL TECHNICAL COLLEGE BUILDINGS

Chapter 1: The NZEB retrofit of Regional Technical College buildings: Introduction

1.1 Background

"Architectural knowledge is contextual. Architectural knowledge derives its relevance from the specific physical, environmental, historical, socio-cultural, and economic environment in which it is applied. Architectural knowledge becomes meaningful only when put in its context" (Foqué 2010). Whether we are talking about buildings designed and constructed 100 years ago, 50 years ago or today, the artefact is bound to the context of its conception and realisation. Buildings are shaped by many forces (Fitch 1976)[1] from the mundane issues of finance, to "architectural metamorphosis to the social, technological and political history of the day" (Lewis 1977)[2].

1.1.2 Purpose

The purpose of the study is to examine the socio-technical forces that impact design decision-making for *Deep Retrofit* performance in building retrofits, and the market adoption of *Deep Retrofit* performance standards like Nearly and Net Zero Energy Building. The research focuses on practice and policy in an Irish economic, legislative and climate context, with case studies based on the recast concrete typologies of the 1970s Regional Technical Colleges.

1.1.3 Topical Factors

Contemporary contexts of global warming and greenhouse gas emissions (GHGs), where buildings account for 40% of GHG emissions (Energy Performance in Buildings Directive 2010)[3], have created a political emphasis on the regulation of building energy performance. EU Directives and national legislations have set increasingly onerous targets for energy conservation in new buildings. However, new buildings only account for 1% of EU building stock each year (Paulou 2014)[4] impacting the potential for GHG emissions. Existing buildings account for 63% of EU building stock predating regulations in 1975, and the retrofit of these buildings is one of the most cost-effective ways of achieving GHG emission abatement (McKinsey 2009)[5]. However, with the total EU building stock renovation rate at only 1.2% per annum and with only 40-60% of this percentage renovated energetically (EU 2007)[6], there exists a potential to increase retrofit intensity to deliver GHG emission reductions by "up to 80% by simple measures, e.g. better insulation of the different components of the existing building stock" (Fraunhofer 2009)[7].

The buildings of the 1960s and early 1970s were created in a vastly different context to today. The commercial buildings that are still occupied today, but which were originally constructed 40-60 years ago, are approaching or have passed the end of their renovation or replacement cycle – a building renovation cycle is 30 to 40 years on average (Directorate General for Energy 2012)[8]. In all cases the materials and construction of these buildings represent an embodied energy: the sequestered CO^2 in their materials and construction still has an environmental value today. In the demolition, disposal and replacement of an existing building additional CO^2 is released. In its employment, CO^2 is released into the environment as a result of the building's operational energy consumption. The amount of emissions released can be directly attributed to the energy efficiency of the building envelope, design and services. The focus of this research is the gross reduction of CO^2 emissions from buildings through the reinvestment of embodied energy in retrofit and the reduction of CO^2 emissions as a result of operational energy consumption savings. Whilst sequestering CO^2 through deep retrofit is a strategic outcome within the general thrust of the study, much extant research exists in this area. Therefore, we will be examining the specific contribution of CO^2 emissions from operational energy, and strategies for its mitigation through the *Deep Retrofit* of buildings. Deep Retrofit is defined by the Rocky Mountain Institute[9] as "a deep energy retrofit is a whole-building analysis and construction process that achieves much larger energy cost savings—sometimes more than 50% reduction— than those of simpler energy retrofits and fundamentally enhances the building value."

It is significant to note that these 1960s/1970s buildings were constructed, in an Irish context, prior to the introduction of building regulations and have a much more inferior operational building energy performance as a result of deteriorating fabric and poorer elemental standards. This is in comparison to new commercial buildings constructed to comply with current building regulations (Part L 2008). Sixty per cent of the EU27 building stock predates 1975 (EU 2007)[10]. Half of Ireland's occupied commercial building stock is pre-regulation (Slater 2014)[11]. The inferior energy performance of these buildings contributes both to higher operational energy running costs and higher GHG emissions than new buildings. However, when making capital investment decisions, building retrofit investment may not be factoring in operational energy savings, increased building lifespan added capital value, and macro-economic issues such as GHG abatement (Steinmüller 2008)[12]. PROBE (1995-2002)[13], CarbonBuzz (2010-2016)[14], Blomsterberg and Engvall (2011)[15] and Steinmüller (2008)[16] also all point to technical deficiencies and a lack of experience with the design of buildings to achieve measured low-energy and good environmental performances.

The Global GHG abatement cost curve (McKinsey 2009)[17] for the Buildings sector clearly identifies a high potential for cost-efficient emissions abatement through building retrofit. *Deep Retrofit* can be defined as a building refurbishment strategy where very low-energy building performance is the set goal, complemented by good thermal comfort and good indoor air quality. Deep retrofit strategies can contribute to Ireland's targets to meeting EU Green House Gas EU emission abatement commitments. A 2012 EU funded report[18] on how to refurbish all buildings by 2050 highlighted key issues with the adoption of low-energy retrofit. The report indicated that the following issues were contributing to market failures in the adoption of deep retrofit:

- Government-led energy price controls,

- A lack of environmental cost externalities embedded in building energy consumption,
- An over-emphasis on capital cost over operational cost savings,
- Uninformed or unqualified development decision-making.

Blomsterberg and Engvall (2012) warned that technical issues and systemic issues were barriers to low-energy building, caused by "insufficient competence to build, design mistakes, small market, unclear or lack of specifications for low-energy houses, no life cycle perspective, lacking incentives, high construction/investment costs, inadequate certification/standard/regulations, inadequate availability of products and inadequate cost estimates and financing".

Addressing a low policy Intensity (Fraunhofer 2009) and responding to the targets set down for the Kyoto protocol, current EU Directives, the *Energy Performance in Buildings Directive 2010* (EPBD 2010) targets *Nearly Zero Energy Building performance* (NZEB) of member state (MS) public buildings by 2019 and non-public buildings by 2021, including deep retrofits (retrofit being defined subsequently as being over 25% envelope retrofit-EPBD Implementation Group 2012[19]). However, contextual issues of the technical capability, regulations and other market barriers may impact the potential to achieve Deep Retrofit performance levels like nearly and Net Zero energy (nZEB and NZEB) performance and the resultant GHG emissions targets.

For the purposes of this report, 'nearly Zero-Energy Building' (nZEB) "means a building that has a very high energy performance"(European Union, 2010)[20], "where the balance of energy needs <u>can</u> be supplied with renewable energy technologies" (Pless, S. & Torcellini, P., 2010)[21] produced on-site or nearby.

For the purposes of this document, and to avoid confusion, it is important to define the difference between nearly and Net Zero energy building performance in deep retrofits. A Deep retrofit involves the upgrade of the building fabric, extending its lifespan and typically includes external insulation, triple glazed windows augmented with heat pumps (Department of Communications Energy and Natural Resources 2015)[22]. A 'nearly Zero energy building' (nZEB) is a deep retrofit, which has achieved a very low level of remaining energy demand (up to 80%) by using energy conservation measures. A 'Net Zero-Energy Building' (NZEB) has met the balance of energy demand with renewable energy (usually produced on site where there is a lack of grid connection) measured over a calendar year. Throughout this report nZEB is used in the context of Irish building standards and EU legislation/policies, and NZEB is used in the context of overall energy performance targets in the pilot-project and design practice.

1.1.4 Legislative Challenges

Although Net or Nearly Zero Energy performance buildings are not new concepts (Korsgaard and Esbensen 1977)[23], at the beginning of the research (2010) there were no NZEB, or measured NZEB, retrofit exemplars in Ireland, and NZEB had yet to be defined in an EPBD context. Over four decades, technologies and strategies for low-energy buildings have progressively advanced through exemplar buildings. Environmental performance issues have been improved, along with the performance and cost-efficiency of technological solutions. However, there remain few measured nZEB or NZEB or low-energy building exemplars in an Irish context and a lack of wider market adoption of low-energy NZEB strategies for retrofit in a non-dwelling context (Department of Environment Community and Local Government 2012)[24].

The context of global warming, the Kyoto Protocol and COP 21 provide excellent social and legislative contexts for abatement demand; however, as this study revealed market adoption issues would still appear to persist.

Perhaps the lack of a consistent definition of nZEB (Sartori et al 2012)[25] or the lack of specific criteria for an nZEB building has, in itself, created a barrier to market adoption (Sartori et al. 2012). The term *Nearly Zero*

Energy Building (NZEB) was adopted by the EU in the recast of the Energy Performance in Buildings Directive (EPBD) in 2010, which sought to address the widening EU policy gap in meeting EU Kyoto Protocol commitment on CO^2 emissions abatement (Fraunhofer 2010).

Reducing GHGs by 20% (below base-year levels) over the assessment period to 2020 is a primary target of the Kyoto Protocol. Buildings account for 40% of the EU energy consumption, and "new buildings account for only 1% to the total European stock each year" (Paulou 2014). The EU refined the EPBD legislation in 2012 and published guidance for cost-optimal nZEB calculations to EU Directive 244/2012 (European Union 2012). The UN signatories to the COP 21 framework agreement in 2015, which included EU member states, accepted that there was a "significant gap between the aggregate effect of Parties' mitigation pledges in terms of global annual emissions of greenhouse gases by 2020, and aggregate emission pathways". Indeed, the EU led the A*mbition Coalition* seeking "to reduce greenhouse gases by at least 60% by 2050 compared to 2010" (European Union 2015)[26], which will require the diffusion pathways like EPBD 2010 for building retrofit and a wide market adoption of nZEB strategies.

EU Directive 244/2012 was transposed in member state reports on cost-optimal nZEB for new-build and retrofit in 2013 (and subsequently augmented in 2015 in Ireland, with additional calculations required by the EU). The Irish calculations are intended to inform a review of the National Energy in Building Regulations Part L 2017 (buildings other than dwellings). This review would see the revision of the 2002 regulations governing retrofit, to deliver minimum cost-optimal nZEB building standards and would be an important potential market driver in demand for Deep Retrofit. The revision of these regulations will have a critical impact on market behaviour guiding design solutions to either conserve energy through demand reduction, or reduce delivered energy through the greater efficiencies of active systems, or a combination of both strategies.

Irish Cost-Optimal Calculations (2013 & 2015) recommend that the most cost-optimal approach to nZEB for retrofit require no envelope retrofit, potentially leaving elemental U-values at 2002 levels. This would represent a significant deviation from the best practice approach of Passive House Design, which is based on demand reduction through a highly efficient envelope design, a key exemplar identified by the EU to inform the recast of the EPBD 2010 (Hermelink 2012)[27]. Passive House Design is a key design methodology used to achieve very low building energy performance in new-build and retrofit. Although initially designed for residential applications, it has been used in commercial applications and *Deep Retrofits*. As a building approaches its renovation cycle it can suffer from a failing envelope, high air-infiltration, conductive heat loss, poor thermal comfort, radiant thermal asymmetry and potentially poor air quality for a given occupancy. EU directives, cost-optimal calculations and national building regulations all have an impact on design stage solutions for *Deep Retrofit* and the potential for GHG abatement. The design stage also faces challenges in delivering a measured *Deep Retrofit* performance levels.

1.1.5 Design Challenges

Although definitions vary, '*nearly' or 'Net' Zero Energy in Building* performance is essentially about creating a very low-energy consuming building, whose remaining energy balance can be met by site-produced renewable energy. There has been a gradual evolution of a definition for NZEB performance (Torcellini et al. 2006)[28] and a variety of designations; Net Zero Site Energy, Net Zero Source Energy, Net Zero Energy Costs, Net Zero Energy Emissions, and Nearly Zero Energy Building. "There are many common definitions such as 'A Net Zero Energy Building (NZEB or Building) is a building that has zero net energy consumption and zero carbon emissions over the course of one year... The strategies for implementing NZEB are to first reduce the demand for energy through energy efficiency and then increase supply of energy from renewable sources" (Hyde et al. 2012)[29]. In Ireland (2016) the lack of grid connections and feed in tariffs make site renewable energy a critical part of NZEB performance rather than off-site renewable production. The EU defined its own terminology as '*nearly Zero Energy Building'* (nZEB) in 2010; however, an actual whole-building performance was not set at that point in time. The EU decided to adopt a *Cost-optimal nZEB* in 2012 with whole-building performances to be calculated for specific building uses in member states.

Achieving a measured *Nearly Zero Energy Building* retrofit performance (2010) can be difficult to achieve as aspects of the building's typology including form, orientation and location are fixed. Barriers to NZEB adoption have included:

- A lack of clear information,
- The division of capital investment and operational cost in investment decision making,
- Uncertain future energy prices, (Jaffe et al. 1994)[30]
- A lack of definitions and financing models,
- Misplaced incentives, misinformation,
- "Gold-plating".
  (Golove 1996)[31]

"…and potentially design team process problems, such as a lack of detailing validation through simulation modeling for measurable performance, the lack of accessible software for architectural practice and adequate training" (Attia 2013)[32].

Technical solutions for NZEB retrofit have faced challenges with poor resultant indoor environmental qualities since the first Zero Energy House in Stockholm in 1975 (Esbensen and Korsgaard 1977)[33]. Indeed, poorly considered solutions have led to poor interior environmental conditions which "can easily unnecessarily give low-energy buildings a bad reputation, which can be difficult to overcome" (Blomsterberg and Engvall 2011). Passive House Design has illustrated, tested and measured integrated energy conservation and technology solutions with breathable super-insulation (Shick et al. 1979)[34] and mechanical heat recovery ventilation. Despite this, Passive House Design has not succeeded in wide market adoption, and remains an elective standard (Boermans et al. 2000)[35].

From early surveys on energy performance (1986), Erhorn has significantly contributed to the dialogue on market demand for NZEB retrofit methodologies. He identified that achieving NZEB performance through retrofit required an essentially multi-disciplinary collaboration involving the coherent design integration of fabric envelope retrofit, active systems, commissioning and post-occupancy management to deliver a measured low-energy outcome (Erhorn 2008)[36].

Erhorn breaks down retrofit strategies into building envelope, heating systems, ventilation systems, solar control, cooling, lighting, electrical appliances and operational management. He establishes that integrated retrofit concepts include "the thermal envelope and the services installations [which] lead to better cost-efficiency" (Erhorn 2008)[37]. He criticises the subdivision of responsibilities within the design team, disconnecting retrofit solutions from indoor air quality, and highlighting the need for more demonstration projects.

The Passive House Institute (2011)[38] introduced the *EnerPHit Standard[39]* in 2013 for building retrofit (the *EnerPHit Standard* was originally designed for residential applications). For the retrofit of existing commercial applications, significant differences in occupancy profile and internal heat gains potentially make the importance of passive winter solar gain less of a factor and the importance of summer cooling more important. In public education buildings like the original 1970s precast concrete RTC buildings in Ireland, current guidelines do not allow for mechanically assisted ventilation outside of specialist rooms such as laboratories (Department of Education and Science 2008)[40]. Therefore, *Passive House* and *EnerPHit Standards*, unlike NZEB, have a more limited application in such typologies.

Lam et al. (1999)[41] highlighted that design teams were made up of the different disciplines of engineers and architects, whose decision-making could become internalised along disciplinary demarcations, and that architects often relied on 'rule of thumb' solutions, rather than being quantitatively specific. Attia reported that architects were less likely to adopt or use building simulation tools in measuring the performance implications of design strategies. Nolte and Strong (2011)[42] highlighted that "few architects and designers were familiar with how to specify low-energy renovation"[43]. Boermans et al. (2000) warned that NZEB expectations may not be reached because of the limited "know-how and number of professionals" available, citing less than 1% of buildings in Germany built to passive house standard (NZEB is not necessarily equivalent to a passive house but close to the energy level of passive houses in new build)[44].

This raises the question of the potential of buildings to be retrofitted to a low-energy or NZEB standard. Research indicates technical issues within the design of buildings and the potential for performance gaps. Gaps in existing literature raise important research questions: Do the commercial buildings approaching their renovation cycle have the potential to achieve a measured NZEB performance? What exactly is that target and what is needed to enable design practice to achieve those targets?

1.1.6 Contextual Issues

The Irish non-dwelling buildings designed and constructed between the 1960s and 1975 were all pre-regulation and as such did not have to conform to any energy standards in their design. Since 1975, design exemplars, regulations and energy conservation priorities have changed design practice. However, PROBE Studies (Bunn 1998)[45] and Carbon Buzz (CIBSE 2012)[46] still highlight the existence of technical or systemic problems that impede *Deep Retrofit*. At the beginning of the process in 2010, this research sought to question how architectural practice had developed, and if an overemphasis on the aesthetics and composition were leading to a deficit in performance-oriented building design, building physics knowledge, technical ability or architectural priority for energy in buildings. This research is important in identifying the key motivations of the actors of the socio-technical process of design (Marszal 2011)[47], identifying potential gaps in the architectural design process, whether that be in education, tradition, stylistic emphasis, priorities, communications, technical competence, brief, or budget constraints.

Another important question that arises is the potential of the steel frame or concrete frame modular buildings of the 1960s and 1970s to be deep retrofitted, extending their lifespan, improving interior environmental conditions and addressing redevelopment costs. Whilst aging buildings still have an embodied energy, their envelopes are failing, raising the questions: Do either steel frame or concrete structures suit an extension of lifespan? Are there concealed issues that would influence a retrofit solution or create specific risks? Would the market readily adopt such solutions?

1.1.7 Geo-Political Challenges

The oil crisis that spanned the winter of 1973 resulted in the creation of the International Energy Agency, with Ireland as an original co-founder in 1974. The IEA initially focused on energy security and helped research into building energy conservation, leading quickly to a succession of low-energy exemplar projects in Europe, Canada and the US. However, changing political priorities and the international cost of oil energy created barriers and market failures for energy-centric design and renewable technologies throughout the 1980s. Initially the cost of new technologies associated with building energy conservation and renewable technologies remained high until wider market adoption brought efficiencies to production. Political support for new low-energy technologies is particularly important in increasing market size, driving efficiencies and lowering costs. For example, photovoltaic costs are 100 times cheaper in 2015 than they were in 1977 (Cleantechnica 2016)[48], and wind-powered electrical production is now as cheap as oil-fired production (Randall 2015)[49], without externalities being considered.

Despite Kyoto, COP 21 agreements and the recasting of the EPBD in 2010, Ireland has not revised retrofit standards since 2002. Diminishing incentives (SEAI 2012)[50] for building retrofit, the lack of available credit for investment (Duggan 2013)[51] and the fractured nature of the market have seen large drops in the pursuance of grants for the *Deep Retrofit* of homes (Sinnott 2010)[52]. The combination of low policy intensity, a poor level of building energy standards and a lack of incentives have all contributed to market barriers to low-energy building, which has had a knock-on effect on GHG emission targets. This research explored the development and role of legislation in the context of activating a greater level of market adoption of *Deep Retrofit* buildings in Ireland, from the first oil crisis in 1973/74 up to 2016 and projecting forward toward 2020. Legislation and building regulations were initially examined, as part of this study, to forecast the potential targets of the nZEB standards between 2010-2020. Subsequently, legislation was examined to identify the potential impact of the Irish nZEB cost-optimal calculations on the revision of building regulations Part L (2017) for retrofit. Potential changes to Part L 2017 could have a direct impact on design solutions, and design team decision-making, shifting the selection of energy conservation measures to focus on passive-first or active-first solutions. The political factor was examined to investigate the most appropriate policy actions required to improve the market adoption of Deep Retrofit in the context of the EPBD 2010, in Ireland.

1.1.8 System Challenges

PROBE studies (Irwin et al. 1999)[53] highlighted the technical issues with architectural design solutions in matching the design stage energy performance estimates with measured post-occupancy performances across a wide variety of building types. The various PROBE studies demonstrated a variety of problems from façade design, solar heat gain, overheating, poor mechanical design, equipment-related heat gains, occupancy profiles and poor post-occupancy system management, often leading to thermal discomfort and poor air quality.

In 2008 Carbon Buzz (CIBSE 2012)[54] was established between the

Chartered Institution of Building Services Engineers (CIBSE) and the Royal Institute of British Architects (RIBA) to collect post-occupancy data anonymously for comparisons with predicted design performance. Post-Occupancy Evaluations (POE's) have not become common practice in the design of buildings (Hadjri et al. 2009)[55] and designers are rarely retained to have a continuous involvement in the building design and operation post-occupancy (Zimmerman et al. 2001)[56]. Carbon Buzz consistently records median post occupancy energy consumption close to, or more than twice the projected design stage energy demand targets, attributing gaps primarily to unregulated loads or general equipment loads (plug loads). Menezes et al. (2012)[57] argues that current modelling methods are unable to represent actual energy use and operation of buildings, due to systemic demarcations created by EPBD, regulations and a simplified Building Energy Model (sBEM).

A systems boundary exists within building energy, separating fixed building electrical loads from process (unfixed or socket) loads. European energy directives in buildings legislation are subdivided into two regulatory areas: Directive 2010/30 Energy labelling for plug-in devices, and Directive 2010/31 Energy in Buildings. The artificial demarcation of Directives is reflected in national building regulations, resulting in the design stage projection of fixed technical systems loads (lighting, ventilation and heat pumps) overlooking the demand of general unfixed service loads within the building, which contributes to operational costs reflected in electricity bills. Energy Rating Certificates, which are required for all public buildings, measure a building's post-occupancy energy consumption from billed energy (rather than its design elemental values, active service packages and renewable contribution, as the Building Energy Rating (BER) certificate does), which includes plug loads leading to actual and perceived performance differences between projected and post-occupancy energy in buildings. This can lead to a perception issue, which, as Blomsterberg and Engvall (2011) noted can be difficult to overcome.

Reusing existing buildings at the end of their lifespan provides an excellent opportunity to reinvest embodied carbon and, as McKinsey identified, building retrofit is one of the most cost-optimal methods for GHG abatement. The successful application and adoption of NZEB solutions face a number of legislative, systemic and design practice challenges: the subdivision of total demand energy in buildings into separate EU Directives, low-intensity retrofit energy regulation (Part L 2002), the capital/operational cost divide, issues with design stage solution integration and a poor level of post-occupancy evaluation.

Solutions to an individual element of the problem set must be considered in the wider context of the systemic issues. Devising optimal design solutions may not be cost-optimal and therefore may not be adopted by the market. "A measure or package of measures is cost-effective when the cost of implementation is lower than the value of the benefits that result, taken over the expected life of the measure [...] Future costs and savings are discounted, with the final result being a 'net present value'. If this is positive, the action is 'cost-effective' (for the particular set of assumptions used in the calculation). The 'cost-optimal' result is that action or combination of actions that maximizes the net present value" (Aggerholm et al. 2011)[58].

Without sufficiently higher policy intensity through improved building energy conservation standards, Ireland risks the potential for market failure of widespread Deep Retrofit adoption. Regulations that favour active service-based solutions (e.g. low-energy occupancy, control lighting, photo-voltaic (PV) systems, high efficiency condensing boilers, solar water heating, air/ground source heat pumps and combined heat and power (CHP)) run the risk of ignoring envelope degradation and may result in poor internal environmental conditions. Ignoring the real impact of plug loads in the demand mix may impact both post-occupancy performance and the appropriate selection of renewable energy solutions, leading again to negative market perception issues. Therefore, the research did not focus on one part of the problem of delivering NZEB retrofit to buildings (other than dwellings) in an Irish context, but on all the forces that shape the solution and its market adoption. This is a systems design approach, which takes a holistic view of a given problem, drawing on the tacit knowledge and experience of the researcher, seeking to address the knowledge gaps to achieving a measured NZEB retrofit performance and market adoption of the same.

Ireland has a very high level of carbon emissions as a result of building construction and operation (National Economic and Social Council 2012)[59]. There is also a low penetration of NZEB buildings in Ireland[60] (Burgess 2015). Despite the growing interest in Passive House Design in Ireland there are no recorded or published measured commercial NZEB retrofit early-adopters to act as exemplars to industry and practice (2012). The potential for non-dwelling buildings to achieve NZEB performance through retrofit has not yet (prior to this research) been established in an Irish environmental context.

Deep Retrofit performance levels like nZEB would represent a significant improvement on the Irish minimum building energy conservation standards of Part L 2002 (governing non-dwelling building retrofit) and Part L 2008 (for new build). The lack of exemplars and low-intensity regulation might directly impact the potential for design practice experience in achieving measured nZEB or NZEB performance in an Irish context. Low-energy intensity regulations, falling energy conservation incentives (SEAI 2012), financial barriers, and split incentives (the separation of capital and operational cost models) have resulted in barriers to the low-energy renovation of building (Poulou et al. 2014). Poulou argues that only a thorough understanding of "these barriers will help member states define the right strategies and implement innovative approaches to address them".

1.1.9 Knowledge Gaps

Existing research has identified critical challenges for *Deep Retrofit* adoption. Steinmüller (2008) reported on the systemic issues that impact client goal setting and the wider diffusion of nZEB policy across the EU. Steinmüller (2008) reports 6 key knowledge gaps in the adoption of low-energy building design:

1. A lack of technical and economic knowledge.
2. A lack of experience with low-energy retrofit.
3. It is difficult to encourage long-term thinking.
4. Energy saving measures and cost benefits accumulating over the lifetime of the building are not fully accounted for in cost analysis and investment decision-making.
5. Capital investment and operational energy are artificially decoupled, thus market prioritisation of low-energy retrofit investment remains low.
6. User-centred design solutions are needed to deliver optimum results.

(Steinmüller 2008)

This thesis builds on a broad range of existing research into energy performance and comfort in buildings, policy and cost-optimality which has been inform by research from the following authors: Aggerholm, Ascione, Attia, Boermans, CIBSE, Erhorn, Fraunhofer, Griffiths, Hermelink, Killip, Ma, Menezes, Nolte, Steinmüller, Torcellini and Voss.

Initially, the research questioned the technical potential for 1970s RTC buildings to achieve NZEB performance through case studies and a pilot project. Arising from the findings from the comparative cross case analysis, the research questioned the market barriers to Deep Retrofit adoption. The research addresses the following research questions (next page):

1.2 Research Questions

RQ1. What were the multivariate factors that shaped the design and performance of the Regional Technical College Buildings in the 1970s?

RQ2. What are the multivariate factors that have led to Ireland's low regulatory policy intensity for retrofit building energy performance?

RQ3. Will the transposition of the EPBD directive result in 'high policy intensity' scenario for building energy retrofit regulations?

RQ4. Can precast concrete RTC buildings, in Ireland, be retrofitted using a natural ventilation strategy to achieve a measured NZEB performance?

RQ5. How can we adapt the design process in Ireland to meet the intentions underlying the EU Directive on near zero energy buildings?

The term 'policy intensity scenario' used by Ecofys and Fraunhofer (2009 & 2010), in advance of the EPBD Directive, refers to the different levels of legislative policy response for *Deep Retrofit.*

1.2.1 Audience

The thesis is aimed primarily at architects, service engineers, interior architects, architectural technologists, facilities managers, quantity surveyors and building owners, but would be of interest to planners, developers, urban designers, building finance specialists, investors and policy developers/ legislators. The outcomes of the thesis are directly informing policy change in Ireland.

1.2.2 The Outcome

The study sets out to contextualise the multivariate factors that influenced the original design of Regional Technical Colleges across Ireland and their subsequent retrofits. The research has also sought to identify the external influences that impact design practice, informing the technical potential to achieve NZEB retrofit through a pilot-project. Once established the study questions the potential adoption of such solutions, by examining the historical forces that retard *Deep Retrofit* building adoption, examining the potential for the EPBD 2010 Directive to improve building regulation policy intensity in Ireland, for building energy retrofit. The research objective is to test whether an existing 1970s precast concrete education building can be retrofitted to achieve a measured site NZEB performance in a cost-optimal manner, in an Irish economic, legislative and climate context. Industrialised precast concrete buildings from the 1960s and 1970s are a very common building typology in Irish tertiary education. As they reach the end of their financial and fabric lifespan, outcomes of the research are both applicable and scalable to this typology and beyond. The research sought to develop a working NZEB pilot-project to inform and demonstrate to stakeholders - investors, operators, design practitioners and the construction industry, the potential of 1960s and 1970s buildings to achieve *Deep Retrofit* performance.

The researcher had intended the exemplar to inform practice, and the artefact performance to inform research, in reflective practice. Finally, the transposition of the EPBD Directive in Ireland and the UK is examined, through nZEB cost-optimal calculations to identify the potential for more intensive nZEB standards in Building Regulations Part L 2017 (Energy conservation in buildings other than dwellings). This was done in the context of supporting secondary research to address the question of *Deep Retrofit* market adoption in an Irish context. The *Deep Retrofit* pilot-project, which was located at Cork Institute of Technology (CIT), provided a test bed addressing the technical knowledge gap in achieving a measured nZEB and a validated NZEB performance. The measured results achieved from the pilot-project are directly comparable to recommended standards arising from Irish cost-optimal nZEB calculations. Their comparison informs both the potential for market adoption of *Deep Retrofit* standards and the likely impact of proposed elemental changes (to Irish energy in building regulations, Part L 2017) on national GHG emission abatement targets.

Steinmüller (2012) had highlighted 6 critical gaps in knowledge across the field of low-energy building retrofit and its market adoption. In the context of EPBD 2010 targets, one of the most cost-efficient methods for GHG emission abatement is through energetic building retrofit. However, as noted previously, there appear to be both technical and systemic issues with achieving the targets of *Deep Retrofit* performance. This study focused on the central themes of Steinmüller's and Golove's knowledge gaps.

1.2.3 Study Themes

1. Historical architectural analyses (contextualising the priority of energy in architectural practice to identify potential barriers in experience or knowledge) *Knowledge Gap #1*
2. Mapping the origins of *Deep Retrofit* building design (the development of *Deep Retrofit* building design, identifying solutions, problems and barriers to the *Deep Retrofit*) *Knowledge Gaps #1 & 2*
3. Historical typology analyses (the development of the design of RTC buildings, their commonality, technical potential and suitability to low-energy retrofit) *Knowledge Gap #2*
4. Socio-political legislative forces (examining the social, technical and political forces that shaped architectural and capital investment decision-making since 1973) *Knowledge Gap #3*
5. Capital investment and cost-optimal analysis (examining the role of investment decision-making, life cycle, cost-optimality and implications

for Part L 2017, to identify their potential to influence market adoption of NZEB for retrofit) *Knowledge Gap #4 & 5*

6. Case studies (carrying out case studies of previous retrofits of a pre-1975 building typology to analyse the client priorities, solutions and the use of any cost-benefit analysis in capital investment stage) *Knowledge Gap#2&4*
7. Pilot-project (design, simulation, retrofit, monitoring performance, reporting on results and observations of a low-energy naturally ventilated retrofit of a sample RTC building typology) *Addressing technical knowledge gaps*
8. Concluding observations on the potential market adoption of *Deep Retrofit* within an Irish environmental, legislative and economic context.

1.3 The Methodology

Architecture is a commercial field of applied arts, and it is exposed to many forces, which in turn shape its contextual outcomes. Building design does not easily subscribe to disciplinary boundaries and is not well defined. Foqué (2010) argues that each design challenge has an internal and an external problem, a physical problem and a socio-cultural problem, leading to the need to use the rules of meta-design, where social, technical and economic issues are resolved in a collaborative approach. Unique design problems are matched to related situations, "making the unique familiar" (Foqué 2010)[61] usually referred to in praxis, as precedents. The precedent in the form of a case study and personal experience transforms tacit knowledge (Polanyi 1966)[62] into a personal body of disciplinary knowledge. The product engenders the 'building genome' composing the data that reflects the design process and its *Functional, Formal* and *Contextual Domains*.

Therefore, the establishment of an artefact's context can help explain the influence on the design process by eliciting facts about the building's design and construction. Through reflective practice (Schön 1973)[63] the practitioner can "surface and criticize the tacit understandings that have grown up around the repetitive experiences". This allows for the creation of a learning cycle of knowledge, questioning assumptions, correcting decision-making or altering a process, iteratively improving a solution or context. Schön's (1983)[64] epistemology is a template for practice-based research where a problem, experiment or an action can be both an inquiry and an intervention, deriving new stories and highlighting problems where the researcher is learning through the process of reflection (Schön 1983). Action research building in a reflective practice paradigm accepts that "knowledge is derived from practice, and practice informed by knowledge, in an ongoing process".

Swann (2002)[65] reminds us the design process is iterative; reflection is a tool for analysing design solutions and "synthesizing revised solutions" (Swann 2002). This reflection is often based on the researcher's "shape of tacit understanding built from practical experience of spatial form" (Swann 2002). Foqué (2010) articulating the same point notes that the architect draws from his repertoire of tacit knowledge to make the unique familiar. By intertwining theory and practice, the design process and solutions are constantly analysed "in a transformative cycle where knowledge is derived from practice, and practice informed by knowledge, in an ongoing process" (O'Brien 2002)[66]. To address the research questions, the methodology seeks to establish how the multivariate influences on the product artifact are manifested, so a synthesized solution can be designed. The study adopts a mixed method model of quantitative and qualitative analysis to address what is a complex, multi-stranded topic. Whilst Foqué's knowledge pocket is adapted to create a structured framework for enquiry, cross case comparative analysis, developed from Ragin (1987)[67], Kolodner (1993)[68] and Flyvbjerg (2004)[69], is employed to analyse case studies and a pilot project.

The research is thus divided, not in the detailed analysis of a small technical element of architecture, such as thermal bridging of a component, but on the broad range of forces that shape the artefact at a problem, process and product level. The methodology thus follows a multi-layered approach integrating the various strands of architectural knowledge and applying it to both the technical and systemic problem of *Deep Retrofit*.

In considering the retrofit of case study buildings from the 1960s to 1970s, the research is informed by Fitch's "historical forces that shaped the building"[70], linking the "mundane architectural metamorphosis to the social, technological and political history of the day" (Lewis 1977)[71]. The research uses the framework of Foqué's[72] briefing knowledge pocket, which breaks down the components of an architectural project in to 4 main categories:

- *Ethical Domain*
- *Formal/Normative Domain*
- *Functional Domain*
- *Subjective Domain*

The research was mapped through these domains to reflect the past, through the present and into the future; the goal of this analysis is to reconstruct the context in which the case study buildings, Regional Technical Colleges, were designed in 1966/67. By understanding the forces that shaped the buildings, we are better able to evaluate them, understand hidden potentialities, reveal risks, and inform a design solution for an action research pilot-project retrofit. The research was staged (Figure 1.2) into domains focusing on the precedent theoretical and physical architectural forces, immediate architectural precedents, the societal and political priorities shaping the building brief, and the rationalist technological strategies for the construction of precast concrete grid-optimised buildings in the late 1960s and early 1970s. Design Science Methodology and Participatory Action Research in a 'concrete phenomenalism' or operation (Piaget 1970)[73] (see methodology Chapter

2) are employed in case study research of precedent retrofit interventions informing the pilot-project seeking to achieve a measured NZEB retrofit at Cork Institute of Technology's 1974 low-rise concrete frame grid-optimised B-Block. This model of design science and 'action research' encourages researchers to experiment through intervention and to reflect on the effects of their intervention, the implication of their theories" (Avison et al. 1999)[74]. The process of design science (which can be comfortably integrated with action research (Bilandzic 2011)[75] is structured:

• Problem investigation,

• Treatment design,

• Design validation,

• Treatment implementation,

• Implementation evaluation.

A design process was analysed and a solution implemented, with interventions from the researchers in terms of solution performance simulation (where this analysis was absent from the normal design process). The research team, which was made up of architectural, mechanical engineering and building services researchers, focused on different aspects within the pilot-project in a multidisciplinary collaboration; with mechanical researchers focused on aspects of natural ventilation and thermal comfort, and the author (hereafter referred to as the architectural researcher) focused on design process, solution design, fabric performance simulation and net post-occupancy performance. The outcome seeks to derive general principles establishing the possibility of NZEB performance through retrofit.

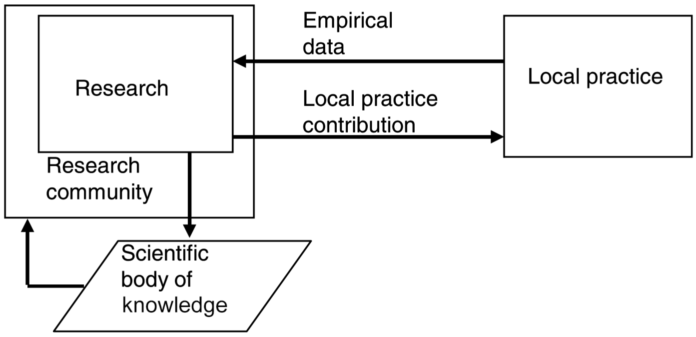


Fig 1.1 Action research and its dual purposes: Local practice contribution and additions to the scientific body of knowledge (Goldkuhl 2006)[76].

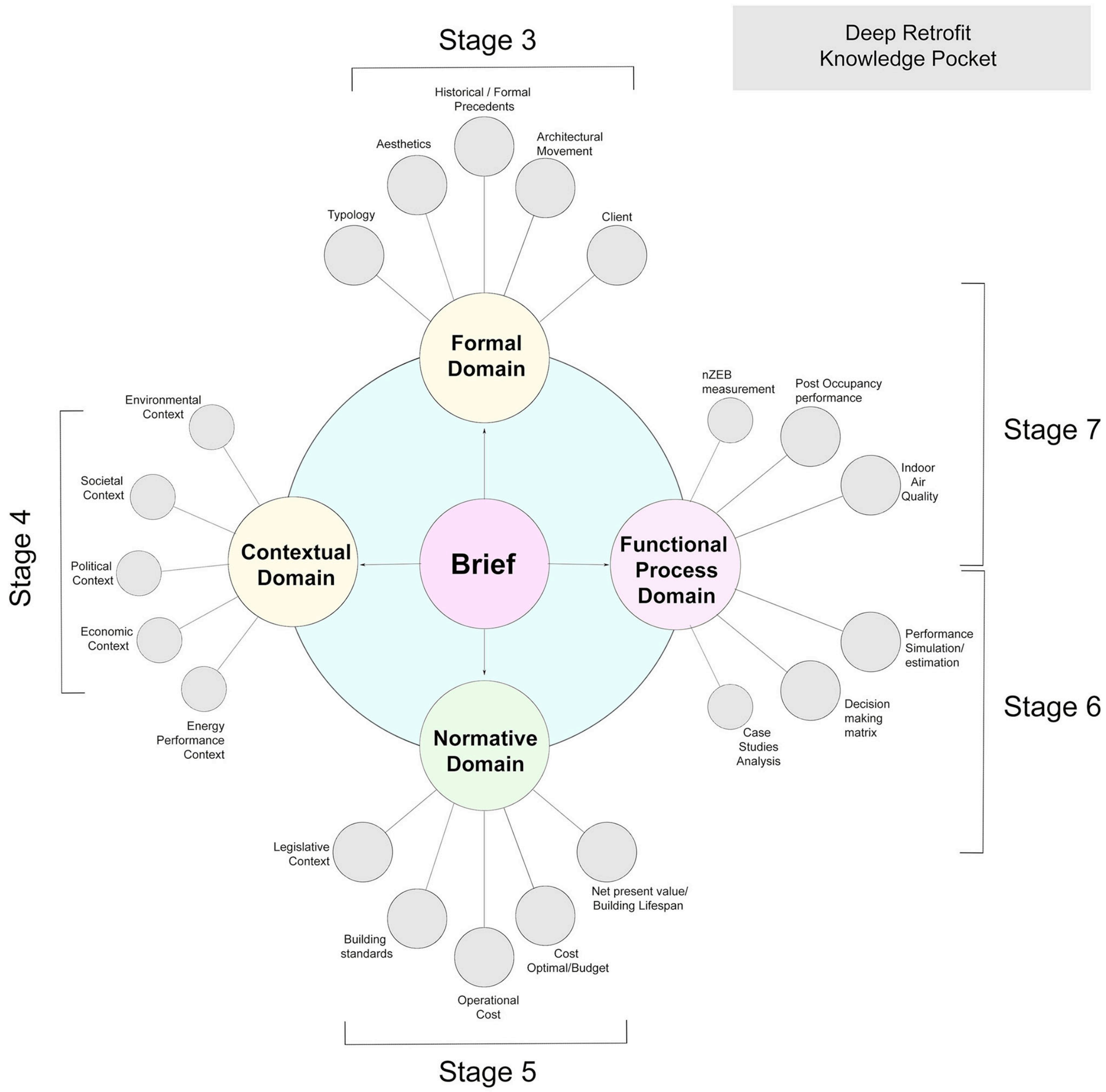


Fig 1.2 Framework for mixed method research

However, as the research will outline a technical solution, it does not represent either the sole solution nor guarantee market adoption. The multidisciplinary nature of the design process does not capture the full extent of actors in the process of artefact outcome. The multi-layered and multivariate nature of building design means that design is intertwined with the needs of the investor and the constraints of the regulator. Therefore, a critical analysis of market barriers to the adoption of *Deep Retrofit* solutions was carried out through a study of the development of legislative implements and their impact on market behaviour, and in turn, design solutions. The development of elemental standards was mapped and compared to the UK (which has broadly similar conditions in relation to architecture, economics and environmental conditions). The application of cost-optimal calculations in Ireland and the UK was compared to the cost-optimal guidelines issued by the EU to identify any variations and discuss how outcomes might impact Part L 2017. The analysis of the research is synthesised into a Sankey map of the forces that influence decision-making in Deep Retrofit, developing barriers to deep retrofit in Ireland from case study analysis, which finally inform a proposed Process for Deep Retrofit which is tested in the pilot project and augmented to address practice barriers. The systemic barriers to *Deep Retrofit* in Ireland are identified, developing on from Steinmüller and Golove, in an Irish context, and potential solutions are postulated.

1.3.1 The case study buildings

Deep Retrofit is a relatively new area of research and practice. Residential retrofit has become a far more advanced field in the past 10 years. Projects like Shaftsbury Park, London by Peabody Trust (2011) and Historic Scotland's Energy Efficiency in Historic technical paper 15 6 (2009)[77] started to look more intensively at the complex dynamics of low-energy building retrofit including air quality and energy efficiency in heritage buildings, technical paper 15 (2015)[78] examined the hygrothermal performance of wall constructions and technical paper 12 (2011)[79] examined the health consequences to building refurbishment.

The inter-relationship of typology, construction type, massing, area/volume ratio, location orientation, glazing ratio, ventilation, air quality, moisture transfer, insulation strategy, solar gains, heat gains, thermal mass, heating and hot water mechanical systems on energy retrofit solutions made the research area complex and nuanced. The solutions for historic buildings will not be similar to modern buildings due to the variation in the building physics of the constructions. In considering both steel framed and concrete framed constructions, variations in thermal mass, thermal conductivity and structural longevity make their retrofit solutions distinct from each other. The post-war shift toward precast concrete construction systems (Intergrid, Derwent or Laingspan) placed them both in a time period (+40 years) where their refurbishment cycle was imminent or overdue, and the precast concrete typology was more suitable to retrofit than its steel predecessors, due to the lack of structural internal corrosion (BRE 2002)[80]. The research adopted this typology and took Regional Technical College buildings as a sample selection for NZEB retrofit, due primarily to their commonality, precedent retrofits, and access.

The Regional Technical College buildings were constructed in 8 locations around Ireland from 1969 to 1977. They were all constructed from a basic common design, varying in size and specification according to the constraints of individual sites. Today all exist and continue to serve a purpose in third level education as Institutes of Technology (IoTs). The nature of their construction does not conform to contemporary building standards, they are poorly insulated and are more expensive to maintain than regulation-compliant buildings (Kelly 2010)[81]. As a result, many of the IoTs who own these buildings have already begun, or are considering redeveloping them in line with current building standards. The low-rise precast concrete buildings are of a common typology and design solutions may be scalable to a broader range of precast concrete buildings of similar age and typology.

The research evaluates case studies, processes, policy and technical building performance. As such the research is both quantitative and qualitative with subjects that include the typological origins, architectural merit, legislative context, society, socio-economic issues, building guidance and building energy and environmental performance as part of socio-technical analysis, to inform the action research (Fig 1.1) NZEB retrofit artefact.

1.3.2 Structuring the research

The research was divided into 9 chapters along the aforementioned thematic lines. As the literature covered a vast array of topics, its review was infused throughout the chapters. Chapter 2 deals with the methodology discussing a mixed model of related research methodologies which include action research, grounded theory, design science, design exercises, case study analysis, the role of artifacts and precedents in architectural practice.

Chapter 3 includes a contextual analysis of the design of the original RTC buildings, examining the forces that shaped the building. The chapter maps the key precedents to the RTC buildings, technological architectural solutions and socio-political contexts to identify the potentialities of the RTC buildings for energetic retrofit. The functional, morphological, technical, environmental, physical and cost attributes of the original design are analysed tracking the main actors, their priorities and influences on the design. It analyses the immediate precedents to the RTC buildings, demonstrating how political, cost and client influences distinguished the RTC design from its predecessors. The chapter highlights the specific differences between the potential of concrete and steel frame buildings for energetic retrofit, and how this might impact extended building lifespan.

Chapter 4 examines the impact of the oil crisis in 1973 and the following policy consequences for building energy conservation. It looks at the development of early technological solutions in low-energy buildings and how changing political leadership stalled the initial development of low-energy buildings in the 1980s. The gradual development of each exemplar and its subsequent influence is mapped through to the Passive House design methodology and building energy modeling. Legislative developments, economic and geopolitical forces are contextualised, illustrating the movement in priorities towards energy conservation in buildings, as global warming becomes an international issue. The development of low-energy buildings is examined to highlight the key principles informing a pilot-project and to establish some of the barriers to the market adoption of low-energy buildings.

Chapter 5 examines the development and structure of the energy performance in buildings directives from 2002 as they relate to energetic retrofit, looking at simulation modeling, financial investment evaluations and how cost-optimal Near Zero Energy Buildings are being adopted in Ireland. The chapter highlights how cost-optimization is calculated in an Irish context and compares the results or findings to similar UK calculations based on similar guidelines. The chapter notes variations from EU guidance, highlighting the impacts on whole-building lifespan, failing envelopes, indoor environmental quality and the potential impact of future building regulations on market adoption of technical NZEB retrofit solutions. The chapter discusses the systemic barriers to the market adoption of Deep retrofit and the impact of potential changes to policy measures on GHG abatement targets in Ireland.

Chapter 6 reports on case studies of the existing 8 RTC building locations, cataloguing their variation or similarity to the original design typology, redevelopments, and modifications since their construction, processes adopted, problems encountered and observations on design team roles. The case studies act as a product analysis establishing a baseline of evidence and performance, informing an artifact-based action research project in chapter 7. The relational networks, priorities, and forces that shaped the decision-making processes of upgrade and redevelopment work are discussed. The benefits or risks associated with the strategies, and technologies employed in upgrades, become a pre-design reflection cycle in advance of an action research project: effectively, precedents informing tacit knowledge. Technical solutions and the use of cost-optimal calculations in capital investment decision-making processes are analysed to act as precedents for a pilot-project design reported on in Chapter 7. A survey of practitioners is reported, supporting findings about the use of cost-optimal scenario analysis and simulation tools in practice. The chapter identifies the main barriers to *Deep Retrofit* in Ireland and develops an augmented design process to address the barriers inherent to the design process.

Chapter 7 tests the proposed augmented design process for deep retrofit in an action research project, where a RTC case study building in Cork is deep retrofitted, with a multidisciplinary research team and project design team. The chapter outlines the roles of the team members and discusses the gaps and barriers arising in the design process, in the context of the identified barriers to *Deep Retrofit.* The chapter is focused both on the quantitative potential of nZEB and NZEB performance through Deep Retrofit and the comparative analysis of decision making in a subsequent retrofit. Cross Case comparative analysis together with content and frequency analysis is used to analyze design team communications and synthesize the main factors influencing the design process, highlighting conflicts and process gaps. The chapter results in the extension and validation of the augmented design process for deep retrofit, with key observations on the systemic challenges for client goal setting in Deep Retrofit.
Chapter 8 draws together the various strands of the research, into a coherent relationship of systemic and design process factors that influence the socio technical process for Deep Retrofit in an Irish economic, legislative and climate context. The chapter maps the various factors in a Sankey diagram, highlighting the systemic and design process barriers to *Deep Retrofit* in Ireland, reviewing the validated 'Design Process for Deep Retrofit' and evaluates the key impacts for government policy.

The final chapter (9) concludes the thesis with personal insight from the author, summarizing his thoughts and conveying the significance of the findings to developing government policies for Deep Retrofit. The chapter illustrates the development of *Deep Retrofit* barriers from Steinmüller and Golove and highlights how the gaps in literature have been addressed in an Irish context. The chapter demonstrates how the research, papers and thesis are influencing government policies, deepening the knowledge and understanding of the barriers to Deep Retrofit, and contributing to knowledge. The appendix is structured to reflect each chapter, including primary research such as interviews, questionnaires, case information, survey data, timeline, reports, published papers, conference proceedings, websites, industry articles, etc. As there is a high level of primary unpublished evidence, this will be placed in a library for future research and interrogation. Each case study in chapter 6 and the detail of the Pilot project in chapter 7 are included in the appendix, as there was not sufficient space in the thesis to accommodate the full body of information without compromising the discussion.

Finally, a 'Fundamental Guide to *Deep Retrofit'*, targeted at building owners, architects and facilities managers, was written to provide an uncomplicated accessible description of the passive and active strategies to achieving NZEB retrofit in a commercial context. Whilst this may be regarded as a non-academic work, the intent of the work is to promote a wider diffusion of *Deep Retrofit* technical strategies. Its audience focus is wide and typically less technically informed, suiting a less academic, simplified medium of communication to establish basic good practice principles and technical solution options.

1.4 Principal findings and results

A pilot-project established that a measured Net Zero Energy Building performance was technically possible through the retrofit of a 1970s precast concrete building. In delivering this performance, thermal comfort was kept within the standards of CIBSE Guide A (CIBSE 2006)[82] and indoor air quality in line with CIBSE guide F (CIBSE 2012)[83], improving indoor environmental conditions within these recommended guidelines. However, whilst demonstrating this performance and its comfort benefits, client capital investment decision-making remained regulation-centric in subsequent retrofits. Building regulations remain a major value-engineering baseline in redevelopment decision-making. Irish retrofit regulations Part L (energy conservation in buildings other than dwellings) remain unchanged from the EPBD 2010 recast and are not energy intensive, remaining at 2002 levels, with elemental U-values similar to 1976 standards. Proposed cost-optimal calculations, which are due to inform the revised Part L 2017 regulations, do not require a change to the elemental U-values, placing an emphasis instead on technical service upgrades, thus effectively reducing production and distribution losses from associated with primary energy demand. Based on the same 'EU Guidelines 244/12' guidance on cost-optimal nZEB, Irish cost-optimal calculations come to different conclusions to the UK, which has broadly similar climate and economic conditions. UK calculations (Department for Communities and Local Government, 2013)[84] recommend the improvement of retrofit elemental U-values broadly in line with Irish Part L 2008 for new build constructions, vastly beyond the performance recommended by Irish cost-optimal calculations.

Cost-optimal nZEB retrofit targets in Irish calculations will do little to address the failing envelope of those 1960s and 1970s buildings, which are at or beyond their renovation cycle. Irish cost-optimal public reference building selection for retrofit scenario analysis was limited to a primary school (median performance of primary school BERs chosen as a baseline), which does not adequately reflect the occupancy profile, equipment-related heat gains or air-conditioning usage of the broader spectrum of commercial buildings. In comparison, the selection of secondary schools and hospitals in UK calculations would demonstrate varied occupancy, equipment density and ventilation profiles.

EU cost-optimal guidelines, which explicitly refer to passive house standards, have left room for member state interpretations and variation. Ireland interpreted the guidelines as only requiring life cycle costing to be applied to the element being retrofitted and not the whole-building value or lifespan. As such, Irish calculations bias towards technical lower capital cost solutions with limited lifespan (20-30 years) and away from fabric retrofit, essentially reinforcing economic investment barriers to Deep Retrofit. Irish calculations explicitly rule out the requirement for fabric retrofit in cost-optimal nZEB performance. The cost-optimal calculations will inform the retrofit elemental requirements for Part L 2017, potentially moving design solutions away from established best practice of super-insulation and improved air-tightness, towards active service-based solutions which minimise primary energy demand line losses and equipment efficiency.

Technical issues with achieving measured NZEB performance in an Irish climate context were found to include deficiencies in knowledge, low-energy retrofit experience, exemplars, education and a lack of building energy simulation software by architects (26%). Significantly, 60% of architects did not believe they had the ability to achieve NZEB performance. It is possible to track some of the current shortfall in architectural knowledge or education back to the low priority placed on building energy and interior environmental conditions in the development of the modern architectural paradigm. The subsequent research, low- and zero-energy building exemplars, established the key principles of low-energy building that exist in the Passive House Design methodologies today.

Geopolitical priorities, changing leadership and oil prices undermined the fledgling market for low-energy buildings in the early 1980s, and demand would not rise significantly until after the Kyoto Protocol of 1998, with subsequent Directives EPD 2002, revisions of national building regulations and incentives for building retrofits. Ireland, which only introduced energy conservation in building regulations in 1997, would only revise this once, in 2002, for the retrofit of buildings other than dwellings, with no changes since the recast of the EPBD 2010. The recast targeted an improved policy intensity required to meet emission targets and Irish regulation for new-build domestic changed quickly in response to this, in 2011. However, retrofit regulations for non-dwelling will remain unchanged until the delayed Part L 2017 revision, which was scheduled to go to public consultation in Spring 2016, but is as yet unpublished, in late 2016.

Further training, a greater awareness of the impact of design decision-making on indoor environmental conditions, the use of simulation modelling, improved commissioning and post-occupancy monitoring, can augment design praxis for *Deep Retrofit*.

The Zero2020 project performs at 86kWh/m^{2}yr, with the remaining energy balance met by on-site renewable production. The retrofit added 40-60 years to the lifespan of the building (equivalent to that of a new building) at 20% less cost than a similar scale and aspect new building on the same site built to 2008 Part L standards, whilst delivering improved indoor environmental conditions for thermal comfort and air quality.

Despite this, case studies have demonstrated that client goal setting for retrofit, is primarily influenced by building standards and the availability of capital. The continued low policy intensity of building energy regulations for retrofit in Ireland, the lack of ESCOs, falling incentives and the lack of investment decision making tools that demonstrate the various benefits to *Deep Retrofit*, are all retarding its market adoption and client goal setting, which constrains design process decision making.

1.5 Directions for further research

The research continues to inform and contribute to national plans for NZEB retrofit policy implementation. The researcher has contributed to the National workshops on NZEB retrofit policy and the development of the “10 points for a better national renovation strategy and an effective implementation plan”[85]. This plan will in turn become the basis of the

Department of Communications, Climate Action & Environment submission to the EU for the revision of the National Renovation Strategy in April 2017. Further research examining the potential impacts of linking property taxes to building energy consumption is currently being developed.

Arising from this research there is the need to develop an online tool for investment decision-making in Deep Retrofit, which demonstrates the costs and benefits accrued. This is the basis of a collective bid for Horizon 2020 funding.

1.6 Benefits of current research

The research has and is directly informing government policy on the revision of building energy regulations for retrofit (part L 2017. It has also significantly contributed to the Department of Communications, Climate Action & Environment submission to the EU for the revision of the National Renovation Strategy in April 2017. The pilot project established the potential for Net Zero energy building performance in Ireland for the first time. The exemplar continues to inform practice and industry, with publications and papers highlighting the barriers to Deep Retrofit in Ireland.

The following is a list of outcomes from the research:

Industry Articles

1. Passive House Plus, 2013. "*Cork Engineering School pilots low-energy upgrade*", Dublin.
2. Irish Building Magazine, 2014. "*Cork Institute of Technology Zero 20/20 Project - Groundbreaking Retrofit*". Dublin.

Conferences

1. German-Irish Passive House and Energy Efficient Buildings Conference (April 2016)
2. 11th Annual AHRA Student Research Symposium, Dublin (May 2014).
3. ACE 2014 Conference Proceedings, Singapore (March 2014).

4. Energy Efficient Retrofit of Buildings Conference, Dublin, Ireland (March 2013).
5. IMC 30 Conference, UCD, Dublin (September 2013).
6. See the Light - Passive House Conference, Ireland (September 2012).

Peer Reviewed Papers

1. Ó'Riain, M., Harrison, J. and McCarthney, K., 2015. '*Zero2020, The Low-Energy Retrofit and Renovation of a Precast Concrete Building in Ireland exploring site NZEB energy retrofit in Precast Grid Optimised Low-Rise Buildings'.* Journal of Engineering and Architecture, 3(No. 1), pp. 1–12.
2. Ó'Riain, M., 2014. '*Zero2020, The Low-Energy Retrofit and Renovation of a Precast Concrete Building exploring site NZEB energy retrofit in Precast Grid Optimised Low-Rise 1960s Buildings'.* ACE 2014 Conference Proceedings, Singapore.
3. O'Sullivan, P., Delaney, F., Ó'Riain, M., Clancy, T., O'Connell, J., Fallon, D., 2013. '*Design and performance of a building envelope retrofit solution for a grid optimised concrete structure: A case study'.* IMC 30 Conference Proceedings, UCD, Dublin.
4. Hyde, R., et al., 2012. '*A Design Framework for Achieving Net Zero Energy Commercial Buildings'*. 2012 ASA (ANZASCA) Conference proceedings.

Book

1. Ó'Riain, M. & Correia, L.G., 2016. Fundamentals of Zero Energy Retrofit Design, Cork: Blurb.

Website/Social Media

1. www.zero2020energy.com (3530 views)
2. https://www.facebook.com/Zero2020energy

The project also won the Irish Design award for Sustainable Design in 2012 from the Institute of Designers in Ireland (Institute of Designers in Ireland 2012)[86]. The research has highlighted important barriers to NZEB adoption, which need to be addressed at all levels: practice, local, national and EU. Key outcomes for this would include a revision of the building codes for NZEB retrofit, public procurement strategies for commissioning NZEB retrofit, financing models and improving practice adoption of simulation as a design validation tool. Creating the first exemplar measured NZEB retrofit in Ireland is a critical first step in demonstrating solutions and costs, as well as highlighting problems to design practice, clients, builders, investors and regulators. The next step will be to implement the findings to increase adoption rates and encourage others to meet and exceed our achievements, helping Ireland effectively reduce GHG emission in existing commercial building stocks.

The next chapter addresses methodologies considered and methods employed for the research process. The merits of reflection practice, action research, grounded-theory, multivariate analysis, participatory action research and the architectural briefing knowledge pocketed are discussed as they apply to the various stages of the research. Because of the multivariate nature of topic domains (referred to earlier), literature is reviewed in the context of each chapter. In the methodology (next chapter) the contribution of seminal authors is addressed in the context of practice based research.

CHAPTER 2

METHODOLOGY

Chapter 2: Methodology

2.1 Introduction

This chapter introduces the research design, discusses the goals, purpose and objectives of the research, and debates the appropriateness of various methodologies. This is followed by a discourse on mixed methods for qualitative and quantitative architectural research.

The following chapter introduces the sample selection and the instrumentation employed in the research study, followed by the goals, purpose and objective of the research study. A mixed method research design is then discussed in the context of the complex variety of forces which shape decision-making in deep retrofit and these methods are mapped out across the thesis in table 2.1. The research is structured following a discussion on potential methodologies. This structure leads to the division of the research into the thematic areas of formal, contextual, normative, functional and process domains that relate to architecture, the design process and client goal setting. An analysis of the multiple criteria that influence deep retrofit decision-making, along with the comparison of multiple precedent case studies lead firstly to the establishment of barriers to deep retrofit in an Irish context and secondly to the development of an 'outline process for deep retrofit'. This process is tested and validated through the analysis of contrasting pilot projects of a case study building, which is subsequently augmented to improve performance outcomes. Content and frequency analysis are adopted to identify the key issues in the goal setting and decision-making processes, which may be retarding better building, retrofit performance outcomes. Research problems and limitations are noted, followed by a statement on the demarcation of research roles in the pilot-project. The chapter concludes noting that the literature review is infused into chapters 3,4,5,6 and 7 due to the broad range of topics examined.

2.1.2 Design Statement

The research design adapts Foqué's (2010) *Knowledge Pocket*, to create a framework for drawing the various strands of research together into a coherent examination of the multivariate thematic areas of influence, with a mixture of methodologies and methods specific to each qualitative or quantitative domain. Formal, contextual and normative domain studies employed a qualitative systematic documentary analysis of existing literature framing decision-making in the architectural process, informed by a significant amount of data collection from primary sources and interviews. A qualitative and quantitative review of the legislative standards, surveys, case studies, performance measurements, a comparison of cost optimal calculations all contributed to the analysis of the normative and process domains. A pilot-project, using a participatory action research (PAR) methodology, included quantitative simulation analysis and content/frequency analysis of design team communications, guided by Wenger (1998)[87] Communities of Practice and Silverman's (1993)[88] Qualitative Data Analysis techniques. The broad study avoids becoming a "mere sketch" of the facts, in addressing "totality" of the evidence (Sartre 1960).

2.1.3 Sampling

Based on their professional involvement with building design, people from the author's Linked-In interest groups and personal contact lists, were individually invited to complete a digital questionnaire. There were 150 responses. The pilot-project involved research, design, construction and client teams limited to a single project over an 18-month period at Cork Institute of Technology. Content and frequency analysis of design team communications and decision-making was compiled using MAXQDA software, using a coding paradigm, to analyse a timeline of email communications and meeting minutes, recorded on a daily basis over 18 months into 2278 lines of open code, grouped into themes, linked in comparative analysis and visualised in maps (400 pages of code are summarised in Appendix 7.10)

2.1.4 Instrumentation

The questionnaire used the online survey instrument *Survey Monkey,* in a single instance questionnaire over one month in July 2015. Case studies compare reported design stage energy performance targets, recording thermal conductivity values of the building envelope, and where existing, post occupancy energy performance. In most cases, the data comes from unpublished design reports from different design teams at 4 former Regional Technical College locations and Ó Fiaich College, in Ireland. The Pilot-Project involved a collaborative research team, collecting energy performance data from existing reports, energy bills and Building Management System (BMS) records to establish a baseline of delivered energy performance that could be compared to case study buildings. Published energy benchmarks such as CIBSE TM 46 were used to compare a wider sampling of university buildings energy performance. An online platform (Carbonbuzz.org) was used to compare post occupancy evaluation of education building energy performance. The Pilot-Project also involved the use of building performance simulation (BPS) tools to project design stage performances of the overall building and component detailing. These included *Trynsys* (used by the engineering researcher), *IES* (used by the consultant engineer), *Therm* and *Wufi* (used by this architectural researcher), and *Therm for Windows* used by the cladding manufacturer. A BMS connected to environmental sensors and energy sub metering recorded post occupancy building performance at the Pilot-Project building for one calendar year (reported by the second engineering researcher). The three researchers' roles were divided along lines of research interests for the efficiency of time and resource, sharing data and reflecting on decision-making. The data compared included primary and delivered energy, carbon dioxide emissions, and internal temperatures. Post occupancy data was published by the second engineering researcher and referred to in this study. The first engineering researcher and the consultant engineer published Trynsys and IES results respectively. Validation of simulation results from Therm and Wufi required three iterations of modelling, forming part of this study

(Appendix 7). Trynsys, IES, Therm and Wufi are all standard software BPS tools used in architecture and to a far greater extent in engineering fields.

Open coding of design team communications was carried out using MAXQDA, which Richards and Richards (1991)[89] argued improves the rigour and transparency of data analysis. MAXQDA also offers "keyword in context" analysis for frequency content analysis using a lexical search function. MAXQDA was used rather than NVIVO or other software as the cost of the software was accessible to the researcher and the researcher found that the learning curve for using the software (using unstructured online tutorials for one day) was shorter than that of the Nvivo software (which the researcher had 3 days of formal training). The MAXQDA software also offered the ability to manage, map and cross reference 2278 coded lines from primary data, from multiple stakeholders through eight separate cycles of coding, reducing and consolidating data and into categories that were linked into a theoretical framework.

2.2 Research Goals, purpose and objectives

2.2.1 Research Goal

The research goal was to devise and test a process for designing building deep retrofits to reduce GHG emissions in line with the EPBD 2010. The research sought to identify the systemic and practice barriers to *Deep Retrofit* in an Irish economic, legislative and climate context. To inform this goal the research set out to contextualise the problem, it's legislative context, previous solutions, best design practice and the market barriers to low energy building design adoption.

Therefore, the following research questions were addressed:

RQ1. **What were the multivariate factors that shaped the design and performance of the Regional Technical College Buildings in the 1970s?**

RQ2. **What are the multivariate factors that have led to Ireland's low regulatory policy intensity for retrofit building energy performance?**

RQ3. **Will the transposition of the EPBD directive result in 'high policy intensity' scenario for building energy retrofit regulations?**

RQ4. **Can precast concrete RTC buildings, in Ireland, be retrofitted using a natural ventilation strategy to achieve a measured NZEB performance?**

RQ5: **"How can we adapt the design process in Ireland to meet the intentions underlying the EU Directive on near zero energy buildings?**

The research goal is to explore technical potential of NZEB retrofit and systemic barriers to its adoption addressing Steinmüller's (2008) reported 6 key knowledge gaps:

1. A lack of technical and economic knowledge.
2. A lack of experience with low-energy retrofit.
3. It is difficult to encourage long-term thinking.
4. Energy saving measures and cost benefits accumulating over the lifetime of the building are not fully accounted for in cost analysis and investment decision-making.
5. Capital investment and operational energy are artificially decoupled, thus market prioritisation of low-energy retrofit investment remains

low.

6. User-centred design solutions are needed to deliver optimum results.

(Steinmüller 2008)

2.2.2 Research Purpose

The purpose of the research was to establish whether it is technically possible to achieve a measured NZEB retrofit post-occupancy performance in a precast concrete RTC building from the 1970s, in Ireland. Specific actions were taken to support this purpose, including context analysis, legislative analysis, cross case comparative analysis (Ragin 2008)[90], quantitative performance analysis, as well as content and frequency analysis of a pilot-project. The viability of the piloted solution for wider market diffusion, and the adoption barriers faced are discussed. Discussions on the findings and the potential implications for future legislation and policy in Ireland occur in Chapter 8.

2.2.3 Research Objective

To address the research goals, various objectives were used to address the various research questions.

The answer to the technical question (4) of the NZEB potential of 1970s precast concrete RTC buildings required a quantitative result. This involved an analytical review of the development of best practice in low and zero energy design, together with precedent case studies to inform viable design strategies for a participatory action research pilot-project, targeting an NZEB energy performance. Within the pilot-project building performance simulation (BPS) tools were used to measure and validate design stage performance, and reflective practice was used to improve measurable outcomes. The pilot-project artefact energy and environmental performances were measured post-occupancy over a calendar year, to establish an answer to question 4.

To address research questions 1 and 2, and to understand how to approach this an NZEB pilot-project in question 4, the research had to establish baselines of knowledge about the artefact that was to be retrofitted: the contexts that informed its design, the multiple factors that influence the design team, the best practice in low-energy design, and the potential barriers to NZEB adoption. To address question 1, the multivariate factors that shaped the design and performance of the Regional Technical College (RTC) buildings, involved a great deal of primary research, discovering many unpublished documents, interviewing key living stakeholders, surveying buildings, comparing building performances from reports and performance data from building management systems. The contextual factors influencing the design of the RTCs required a systematic review of the current state of existing literature, including environmental, legislative, and social/political commentary. To that end, the second objective was to carry out a contextual analysis framing the technical challenge and analyse the results of the pilot-project, in the context existing knowledge.

To address question 3, "will the EPBD directive result in 'high policy intensity' standards in Ireland", was considerably difficult as the legislative environment was developing in parallel with the research study. At the beginning of the research study in 2010, the EU had just published the recast EPBD Directive, and the EU's cost-optimal guidance would not be published until 2012. The first Irish cost-optimal calculations were published in 2013, with UK calculations also published in the 2013. Additional Irish cost-optimal calculations for retrofit were published in 2015.

To answer question 4 required a critical analysis and comparison of both Irish and UK cost-optimal calculations, the methodologies used, their compliance with published EU guidelines, drawing conclusions from the comparison of their results on the potential impacts for changing policy intensity in Irish building energy Regulations. To draw such conclusions also required a longitudinal study of building standards in Ireland since 1976 and geo political factors that can become external factors influencing changing regulations over time. Finally, in the conclusion, the study draws insights from the various strands of research questions, synthesizing findings to elicit likely theoretical practice and policy implications.

2.3 Appropriateness of the research design, discourse, context and rationale

2.3.1 Framing Mixed Method research

The study adopts a mixed method model of quantitative and qualitative analysis to address what is a complex, multi-stranded topic. The issue of *Deep Retrofit* is both a technical challenge for the design process and a systemic challenge for public policy, with impacts on market adoption of optimal solutions. The issue is affected not only by the knowledge, experience and understanding of the professionals in the design process, like the architects and engineers, but also by external factors that influence goal setting by the client.

Jick (1979)[91] argues that such complex issues with multiple influencing factors require a triangulated approach: "One begins to view the researcher as builder and creator, piecing together many pieces of a complex puzzle into a coherent whole. It is in this respect that the first-hand knowledge drawn from qualitative methods can become critical". Jick's approach would allow the researcher to draw the multiple influencing factors together across the broad socio-technical process for Deep Retrofit, from the architectural paradigm, to geo-politics, the policy dependence of an open economy like Ireland on geo-economic conditions, the impact of the geopolitical environmental shift on EU legislative paradigm and in turn national policies for energy conservation, the national economic and legislative context, to specific building energy performance barriers within Irish design practice. The researcher can bring 'firsthand' tacit knowledge and experience to the analysis, synthesis and evaluation of such a triangulated approach, from 20 years of practice in commercial retrofit.

" The fieldworker knows that he knows, not only because he's been there in the field and because of his careful verifications of hypotheses, but because "in his bones" he feels the worth of his final analysis"
Glaser and Strauss (1965)[92]

Such a triangulated approach requiring a mixture of qualitative and quantitative analysis can be referred to as a 'Mixed-Method' approach. Whilst Betzner (2008) highlights that there is no definitive consensus on the theoretical underpinnings of the methodology, he advises that adopting both dialectic and pragmatic method can add value to the conclusions, in developing both accurate quantitative findings (like building energy performance) and in generating new hypotheses in what is a 'complex phenomenon'[93].

Creswell & Clark (2007)[94] justify the use of a mixed method approach where "quantitative and qualitative approaches in combination provides a better understanding of research problems than either approach alone."

Architecture sits at the intersection between the qualitative and quantitative paradigms (Andreas, 2012)[95], between art and science. In practice architects work in a paradigm where there is a constant blend of the qualitative and quantitative, where issues of form and aesthetics meet with performance and cost. The issue of *Deep Retrofit* and its adoption is not simply one of building energy performance, which is clearly quantifiable, but also an issue influenced by the priorities and concerns of the architectural paradigm, education, team interaction and communications at a design practice level. The aspirations and targets set down for a *Deep Retrofit* have costs and benefits, informed by external factors such as economics, legislation and politics at a systemic level. The practice of architecture is akin to the Plato's dialectical process, a counterbalance of competing arguments, requiring a synthesis and resolution.

Plato reminds us of the higher order of the dialectical process, in teasing out the realities of multiple stories to establish the truth. The dialectical process embraces an overview of both rationalist and empirical knowledge, applied through personal experience and practice, as the key to the pursuit of universal truth and higher knowledge. Neveu (2008)[96] argues that architecture seeks synthesis through a blend of theory and practice, or as Fitch (1972) refers, between aesthetics and function. To apply a simply empirical qualitative approach to observing practice would be beneficial to discovering deficiencies in the design process of low-energy buildings; however, it would not examine precedent, test or demonstrate exemplar, explore the impact, or measure its success. The advantage in adopting a mixed methods paradigm would be in its ability to blend both counterpoints of rationalist and empirical knowledge. By using this 'third way' (Alasuutari, Bickman, & Brannen, 2008)[97] the researcher can better converge and validate findings, to create a holistic overview of a complex issue.

Tashakkori & Teddlíe (2003) outlined the processes for mixed method research, using both qualitative and quantitative techniques, in a single research study. They argue that a mixture of congruent methods require a coherency to the subject at hand, rather than an unrelated 'mix and match' approach' unrelated to the subject matter. Adapting Foqué's (2010) [98] knowledge pocket for case study analysis allows the mixed methods to applied to specific related topics (Table 2.1), framed by key domains of inquiry for analysis, synthesis and evaluation (Fig. 2.1).

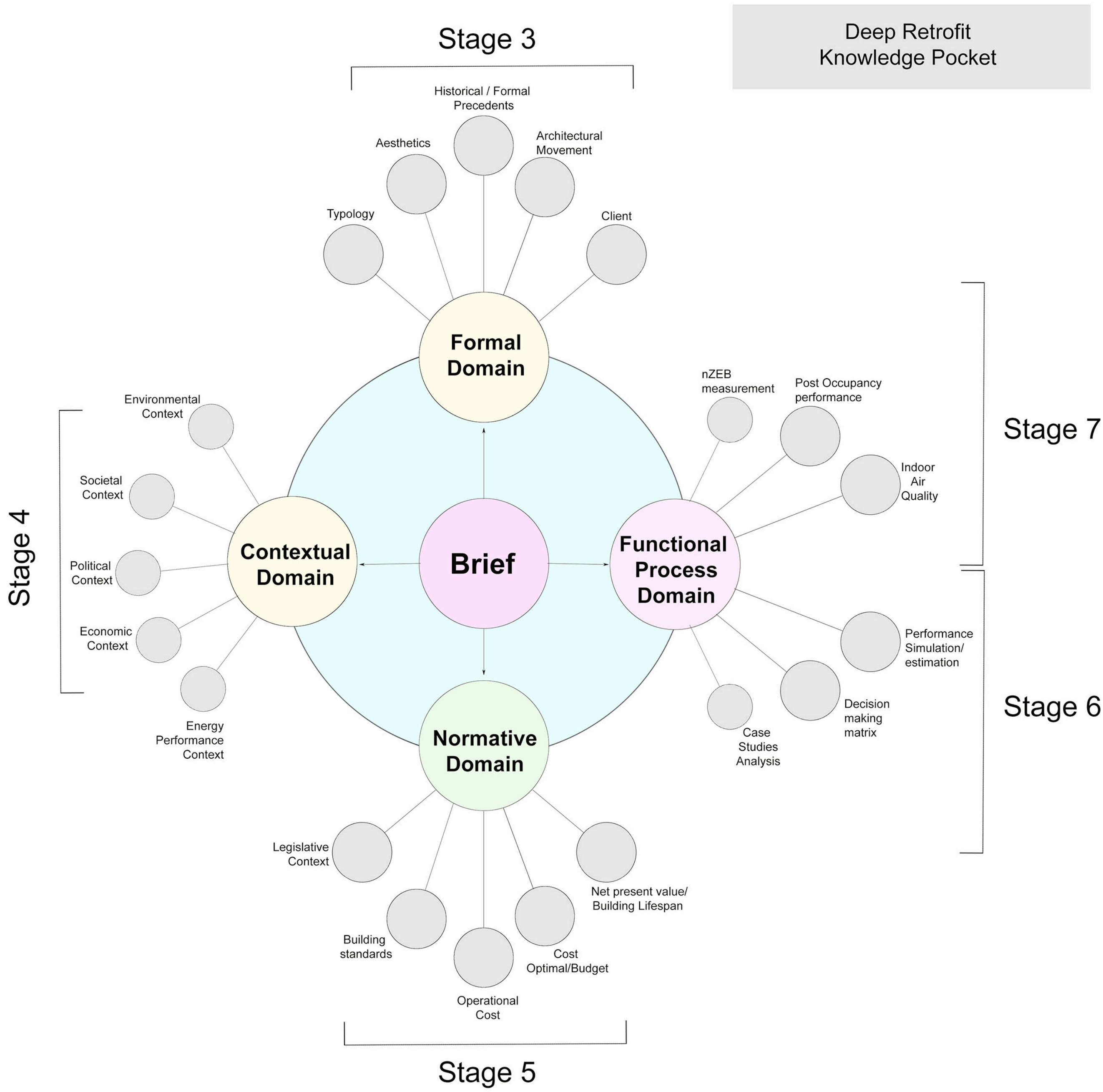


Figure 2.1 Adapting Foqué's knowledge pocket to frame the methodological process (O'Riain 2016)

Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7	Chapter 9
Formal Domain	Contextual Domain	Normative Domain	Functional & Process Domains	Functional & Process Domains	Synthesis, Evaluation & Discussion
Case Study Typological precedents (Qualitative)	Mapping evolution of NZEB best practice from literature Review (Qualitative)	Mapping evolution of EU Directives Building Energy Conservation (Qualitative)	Cross Case Comparative Analysis (Qualitative)	Synthesis of key Process Barriers (Qualitative)	Synthesising factors influencing Socio - Technical Deep Retrofit Process (Qualitative)
A review of the priorities of the Architectural Paradigm (Qualitative)	Reviewing Socio-economic impact oil crisis from literature Review (Qualitative)	Analysing Building regulation & GHG Compliance (Qualitative)	Retrofit Practice Analysis (Qualitative)	Analysis of published design process models (Qualitative)	Evaluating systemic and practice barriers to Deep Retrofit (Qualitative)
Case Study Typological Analysis (Qualitative & Quantitative	Mapping evolution of building energy legislation (Qualitative)	Reporting on Irish Design Practice Survey (Quantitative)	Decision-Making Analysis (Qualitative)	Researcher & Participant Roles	Refining optimal Deep Retrofit Process (Qualitative)
Surveys of the commonality and differences within of the RTC typology (Quantitative)	Reviewing Geo-political/ economic Factors from literature Review (Qualitative)	Synthesising Practice Barriers and analysing existing publications (Qualitative)	Analysis of investor goal setting (Qualitative & Quantitative)	Pilot project, Phase 1 & 2 analysis methods	Validating Research Questions (Qualitative & Quantitative)
Priorities & goals in design of the RTCs in 1974 (Qualitative)	Analysing the Geo-environmental paradigm shift (Qualitative)	Mapping Irish Retrofit Standards evolution (Quantitative)	Precedent Analysis (Qualitative & Quantitative)	Building performance analysis reporting (Quantitative)	
Mapping the stakeholders and decision making of RTCs designs 1966-1974 (Qualitative)	Mapping the origins and influences of EU Directives on Building Energy (Qualitative)	Proposed improvements to Retrofit standards (Qualitative & Quantitative)	Analysis of Learning opportunities (Qualitative)	Simulation & Cost Analysis *(Quantitative)*	
Cost Analysis and Post occupancy surveys of Original RTC design (Quantitative)		Evaluating EU boundary issues (Qualitative)	Analysis of Faults and errors (Qualitative)	Case Content/ Frequency analysing (Qualitative & Quantitative)	
		Analysis of Cost optimal nZEB calculations (Qualitative & Quantitative)	Process Barrier Synthesis (Qualitative)	Conflicts and errors (Qualitative & Quantitative)	
			Visual Mapping an optimal design process (Qualitative)	Synthesising Cases Study analysis (Qualitative)	

Table 2.1 Mapping mixed method analysis across domains and chapters (O'Riain 2016)

Addressing Cresswell's (2007) checklist the research can be broken down into formal, contextual, normative and functional domains (Graph 2.6).

- The 'formal domain' (Chapter 3) examines the evolution of the design of the RTC typology and the shifting relationship of the architectural paradigm with building energy.

- The 'contextual domain' (Chapter 4) triangulates the influence of external factors like international oil prices and environmental concerns on national policy measures for *Deep Retrofit.*

- The 'normative domain' (Chapter 5) maps the development of building energy conservation standards for retrofit, identifying systemic barriers and their impact or potential impact on the market of *Deep Retrofit.*

- The 'functional and process domains' (Chapter 6 & 7) develops an outline process for deep retrofit addressing established systemic barriers (from Ch.5) supported by precedent and subsequent case study retrofit projects. The process is tested through a retrofit pilot project, further identifying practice barriers and mapping optimal Deep Retrofit processes to achieving technical performances of 'nearly' and 'Net Zero Energy Buildings'.

- Chapter 8 synthesizes the findings from each of the chapters, mapping the various factors that influence goal setting and decision making in the 'Socio-Technical Process for *Deep Retrofit*'. It also addresses research questions, evolving the barriers to *Deep Retrofit* in Ireland, validating the proposed 'Socio-Technical Process for *Deep Retrofit'*.

The various domains require specific methods for analysis, but before we discuss these methods in detail, it is important to address the suitability of the methodologies.

2.3.2 Supporting a reflective practice methodology

Spurred by an early review of Piaget's constructivist reflective cycles of learning, the researcher discovered Dewey's model of experiential learning, which builds on the tacit understanding of the researcher in practice. As the researcher had 20 years of practice experience, the use of a rational praxis in a pragmatic paradigm, where the entire study over a period of 6 years could act as a series of reflective cycles, had the potential to lead to a transformative understanding of the subject at hand. Dialectical reasoning in 'positivist' paradigm was considered, arising from reviewing the works of Plato and Hegel, as a methodology for generating new knowledge from an exploration of the multivariate factors influencing *Deep Retrofit* decision-making. In attempting to avoid a research framework limited through disciplinary centric concerns and architectural bias, the research framework attempts to capture both the internal factors influencing *Deep Retrofit* outcomes and external forces that shape the goals at the outset of the project.

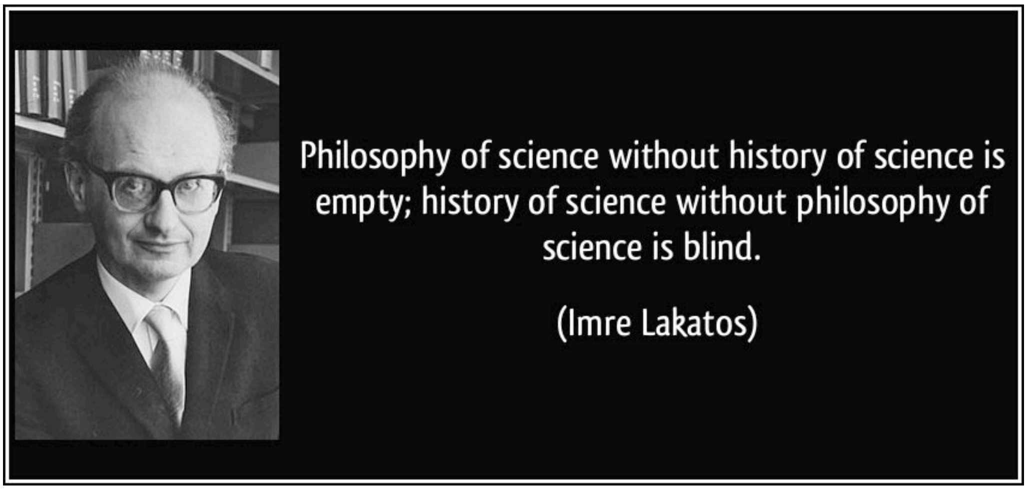
James Marston Fitch (1972) argued that architectural practice was more focused on aesthetic and formal composition, than the environmental performance of the building. Fitch argued that the forces that shape our buildings couldn't only be measured in environmental terms, but also in terms of paradigm bias, education, economics, society, legislation and politics. This is because the context in which a building is designed is not only dependent on the current technology; it is also dependent on;

- Knowledge available at temporal points to solve particular problem sets,
- Budget and aspirations of the client,
- The building's precedents,
- Its legislative boundaries,
- The priorities of the architect and the design team,
- Building regulations,
- National politics,
- Global economics.

This complex web of external influences framed the realities of practice, in the realisation of the artefact.

A scientifically rationalist approach to building energy performance might involve a quantitative study of the physical capabilities of a building's envelope, to minimize heat loss or technically achieve NZEB performance. However, the result would not be pragmatic, as the solution arrived at could be limited to a small piece of the puzzle: a micro-assessment of a macro issue. Architecture, and construction deals with the macro-elements of society and the microelements of architectural detailing. The factors influencing the architectural artefact are thus multi-layered. They can be broken down into 5 fields of tension: contextual, methodological, systemic, competency, and professional.

Plato argued that the "conception of a thing" was, in fact, the "essence of the thing'. Thus, having knowledge of the fields of tension, which influence the conception of an artefact, "enlarge(s) our conception of ideas" (Plato 1941)[99]. Plato claims that holding solely the mathematical hypothesis to a theory, without the ability to impart the conception, fails therefore, in intelligence; yet to depend only on the 'shadow' of opinion also fails to apprehend the absolute truth (Plato 1941)[100].



(Lakatos 1971)[101]

Plato in seeking the truth, advises on reconstructing the story from its "first principles…[and] intermediate steps… to the conclusion" to create a reasoned assessment of the artefact, "implying greater clearness than opinion and less clearness than science, and this [referring to the dialectic], in our previous sketch, was understanding"[102]. Plato's Dialectic draws a centre line between qualitative and quantitative methodologies, seeking a middle domain as Kant (1914)[103] had interpreted.

The research therefore, is not based exclusively on a rationalist science or empirical paradigm, more suiting mixed method analysis, synthesis and evaluation. Scheffler (1965)[104] offers a pragmatic epistemology as a legitimate methodology in the search of universal knowledge. This pragmatic approach is a blended methodology arising from Plato's dialectic, sitting between the rationalist and empirical. Architecture has long been associated with paradigm revolutions, between the empirical and rationalist, demonstrated by the thesis of the Arts and Crafts Movement and the antithesis of Modernism, or the post war (WW2) battle "between the hards and the softs…the Corbusian rationalists and these Swedish empiricists" (Kite 2010)[105]. Paradigm change is also a common occurrence in architecture, with external factors like war, technology, and economy triangulating contexts for such transitions.
Hegel describes the '*Idea'* "as self-contradictory because the 'subjective' is subjective only, and is always confronted by the objective" (Hegel 1830)[106]. The Hegelian dialectic is one of counterpoints, of thesis and antithesis, where opposite positions are explored to unveil the truth. The Hegelian dialectical process offers a mechanism where research can investigate changes or influences on the architectural paradigm, that lead to new positions of synthesis, going beyond myth or bias, to establish the true factors that have influenced transition, revolution or evolution of praxis, potentially influencing similar situations in the present. Mason (2002) identified the need to select a variety of research sample studies that reflected or represented the 'processes, types, categories or

examples" which appear in the wider universe. Bryman (2001)[107] highlights the importance of the 'deviant case' in representing the antithesis to a theoretically defined pattern. Silverman (1993) advises that it is important to seek out negative instances, where cases offer evidence that contradict or challenge the hypothesis or theory. In this way, the deviant can become the Hegelian counterpoint to the theoretical position, potentially unveiling the key drivers or key barriers to Deep Retrofit.

Hays (1998) referred to the architectural discipline as a 'program', which was not autonomous in its historical position, but where the methodology of praxis was subject to various external factors, including "social, economic, political, technological, [and] psychological" (Hays 1998)[108]. This research process, therefore, needed to position and contextualise the influence of multivariate factors on decision-making within, and outside, the design process to identify the 'truth' of which factors are more likely motivate paradigm change towards *Deep Retrofit*.

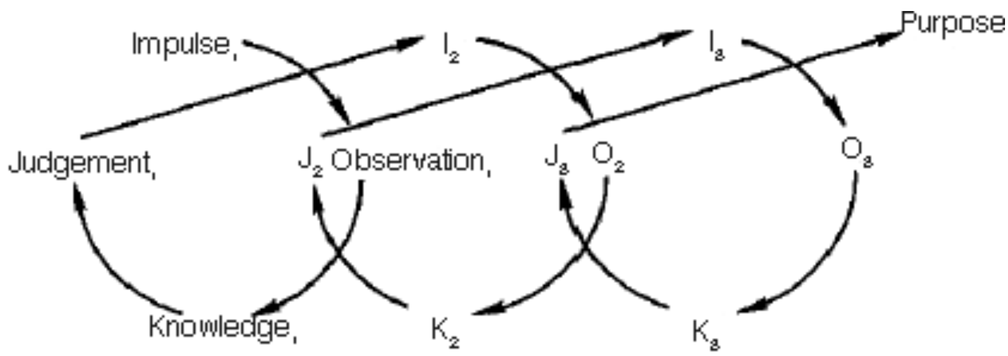
A variety of factors influence decision making in the design process today which can be traced back to issues like the formal bias of the modernist architectural paradigm that informed the design of the original RTCs in 1967, and the oil crises impact on emergent low-energy buildings, legislation, geopolitical events like the cold war and the Chernobyl nuclear disaster (which, again, raised the international profile of environmental concerns); giving way to the Kyoto protocol, which continues to influence the current normative paradigm, and the struggles of praxis to respond to these changes.

Dialectic Method, therefore, would seem to offer opposing viewpoints or counterpoints on a single subject, to establish the truth between reasoned arguments. By examining a wide range of competing factors influencing pre-design stage goal setting and design stage decision-making, as well as a variety the analysis of retrofit case studies (including a deviant case analysis), the research can thoroughly examine assumptions and concepts, improving basic definitions, rigorously re-evaluating pre-conceptual knowledge and questioning theoretical standpoints to arrive at the truth of the matter at hand.

Betzner (2008)[109] "While the dialectic stance prioritizes consciously choosing and engaging paradigms in the conduct of mixed methods research, pragmatically based mixed methods respond not to philosophical tenets, but to a grounded reality of practicality, contextual responsiveness, and consequentiality."

Whilst dialectical reasoning appears to be a very suitable framework for exploring the truths of factors influencing *Deep Retrofit* within mixed method research, it is not without its critics. Sartre (1960) saw the fundamental characteristics of dialectical reason as 'unintelligible', questioning the validity of 'positivist reason'. Sartre saw the limiting of the boundaries of a dialectical study as being of questionable value, represented as a "mere sketch" of the facts, rather than the "totality" of the evidence (Sartre 1960)[110]. This is a fair position and a fair critique; therefore, the research broadened the scope of the analysis to include a broad spectrum of influencing factors rather than just the narrow parameters of the design process, through various temporal revolutions. This allowed the research to address the totality of dialectic reasoning, as Sartre (1960) had argued, whilst allowing opposing positions reveal which factors moved the architectural program, rather than using subjective opinions to represent the superior influence of one factor over another. Genlin (1966)[111] argued that Plato's Dialectic method requires an axiomatic deduction from competing arguments, where 'contradiction' is likely to arse in the study of examples or in the application of a theory arising from the analysis of competing arguments, leading the researcher to reformulate processes 'newly'.

Schön's (1983) epistemology of rational praxis is a template for practice based research, where the method involves a problem experiment or an action, which can be both an inquiry and an intervention, deriving new stories and highlighting problems where the researcher is learning through the process of reflection (Schön 1983)[112]. Swann (2002) reminds us the design process is iterative, reflection is a tool for analysing design solutions and "synthesising revised solutions" (Swann 2002)[113]. This reflection is often based on the researcher's "shape of tacit understanding, built from practical experience of spatial form" (Swann 2002). Foqué (2010)[114], articulating the same point, notes that the architect draws from his repertoire of tacit knowledge, to make the unique familiar. By intertwining theory and practice, the design process and solutions are constantly analysed "in a transformative cycle where knowledge is derived from practice, and practice informed by knowledge, in an ongoing process" (O'Brien 2002)[115].



Graph 2.1 Dewey's model of experiential learning (Kolb 1984)[116].

The ability to bring tacit knowledge, dialectic reasoning and reflective critique together, as Foqué (2010) defined it, which could help structure the examination and analysis of the complexity of a building case, where the body of practice knowledge has a "logic and epistemological autonomy, multilayered in character" (Foqué 2010). This reflective critique thus becomes part of the reasoning in the dialectic method, allowing a greater level of judgement and insight.

The pragmatic paradigm is, as Foqué (2010) offers, "always contextual and contextually bound", reflecting the nature of architectural artefacts, which are contextually bound in the temporality of their initial construction (Foqué 2010). Constructions are manifested, not in socio-cultural, economic and political voids; but instead, occur in different contexts of time, legislation and economics, where we can re-examine case studies to discover linear evolutionary models of typological and design process development. The architectural product engenders the 'building genome', composing the data that reflects the design process and its *Functional*, *Formal* and *Contextual Domains*. Therefore, the establishment of an artefact's context can help explain the influence on the design process, eliciting facts about the building's design and construction. Foqué offers a detailed framework for architectural analysis, where Lawson (1980), Wenger (1998) and Silverman (1993) focus on methods, which could be integrated within such a mixed method framework. It could be argued that Foqué's model centres on the artefact as a repository of knowledge, embodying the design processes and external temporal factors influencing decision-making. Lawson (1980) on the other hand focuses on design practice rather than the artefact. By adopting Lawson's method the research could limit its findings, to those that directly influence the design process and the decision-making within this process rather than examining the totality of the evidence (Sartre (1960). Competing arguments may not be so process bound, with external factors having an impact on client budget setting, building standards and the availability and cost of finance to invest in *Deep Retrofit.*

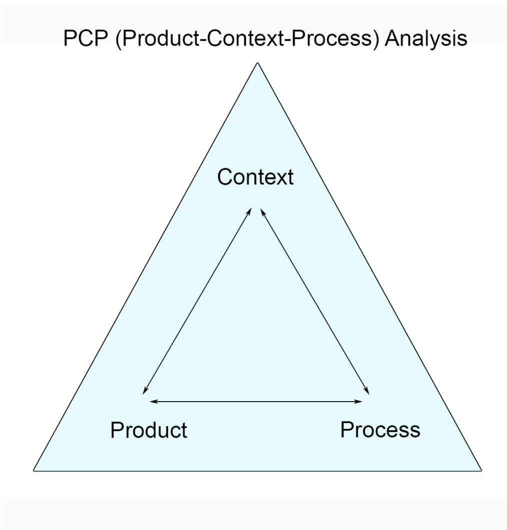


Figure 2.2 Foqué's triangles of architectural research.

Architecture, as Foqué (2010) refers to it, is meta-knowledge, relating to the product, context and process (Figure 2.2). A case study represents an instantiation where disciplinary boundaries are not defined. Examining multiple case studies allows general principles to be derived from comparative analysis. Case studies are a common tool in architectural research and can be used to translate an individual repertoire (Schön 1973)[117] into tacit knowledge and a body of disciplinary experience. Gerring (2007)[118] however, argues that for a typical case to provide a broader insight into a particular phenomenon, "it must be representative of the broader set of cases" (Gerring 2007). Yin (1984)[119] criticised case study method, for its openness to equivocal evidence and investigator bias, with small survey number limiting the validity of scientific generalisation with the length of the study and the quantity of the data becoming unwieldy, disorganised and unsuited to scientific analysis. Hamel et al (1993) argued that by narrowing the parameters of the study, the amount of case studies becomes less important. To address these criticisms, case studies would include 6 primary precedent retrofits narrowed to same typology, one pilot project and a subsequent retrofit, with reference to a parallel retrofit at Birmingham University and a parallel new built at CIT, Cork. The pilot project becomes the deviant case, in that it is dissimilar from the standard practices demonstrated in the other case studies. It could be argued that 'subsequent ' or final case study could be defined as the deviant case, as it contradicts or challenges the hypothesis. The final case is the extreme case in that it demonstrates the defining influence of client goal setting, which is reflected in other case studies. The pilot project on the other hand, uses a unique process with unique outcomes making it more appropriately defined as deviant from the standard cases.

To establish the representative typological nature of the RTCs that are studied here, we must first link them to their precedents, establishing their position, or context, within an architectural evolution, displaying common pattern language and performance traits. However, to focus solely on the artefact would deliver a narrow boundary set of results, ignoring other factors that influence design decisions, which may be critical to future low-energy solutions and policy intensity responses. As Schön (1973) argued, rational praxis may be based on problem solving…"but with this emphasis on problem solving, we ignore problem setting, the process by which we define the decision to be made, the ends to be achieved, the means which may be chosen"(Schön 1973)[120]. Schön's (1973) inference that the 'setting' that may occur prior to the initiation of the design process, could be more important to the design solution than the decision making within the design process itself, therefore sets the wider systemic and practice parameters on which the research study should focus.

The research however, was not limited to a historical study of the topic; an objective of the research was to test the potential of a precast concrete 1970s building to achieve NZEB performance through a measurable experiment. To do this, the research needed a mixed methodology, which could address both the design praxeology and design phenomenology: both the process and the artefact (Cross 2006)[121]. The methodology needed to be able to adapt to the iterative nature of the design process, whilst allowing for case study analysis and quantitative assessment. This is essentially the basis of the argument for a mixed method approach, where qualitative methods are used to contextualise many of the external and internal factors which influence the 'setting' and the process of arriving at a 'solution'.

The apparently separate sections of mixed method research (Table 2.1) require a methodological framework model (Fig 2.1) for the analysis, synthesis and evaluation, with specific methods for each section. The sections are intertwined forces that exert varying influence upon building energy performance over time, allowing the researcher to synthesise and map the seminal barriers to deep retrofit, offer processes to ameliorate these barriers and postulate policy actions that are more likely to successfully impact the market adoption of deep retrofit, given a greater level systemic understanding of their influences.

2.3.3 Methods for cross case comparative analysis of the socio-technical process

The methods thus take a mixed approach to the various domains, with a focus on both positivist reasoning and constructivist observations of the design process, through a dialectic or Hegelian stance, finding a middle ground between thesis and antithesis. The issue of *Deep Retrofit* is limited to the analysis of a single typology with multiple case studies to address critiques of the scientific generalization of findings. To address process and the artifact, the formal, context, normative, function and retrofit processes of Regional Technical Colleges are explored.

Historical method is used in the 'Formative Domain' where primary sources (interviews, measurements, visual documentation, declassified unpublished documentation, drawings, minutes, notes, internal reports and specifications) and other published evidence are analyzed, where the validity, reliability, and relevance of the sources are paramount. This establishes, for the first time, the factual history of the design and construction of the Regional Technical Colleges, and the factors that influenced the artifact outcome between 1967-1974.

Historical method is also used to map the 'Contextual Domain', the socio-economic impact of the oil crises (1973 & 1979) and development of best practice in zero energy building design since 1974, the emergence of building standards in Ireland and the impact of the emerging geo-political environmental debate on European Directives.

In the 'Normative Domain' a quantitative analysis is used to map the evolution of building energy elemental standards in Ireland to allow the researcher demonstrate accurately the policy intensity of retrofit regulations and their impact on goal setting, supporting evidence is drawn from official government reports to project the potential impact of such policy intensities. Quantitative surveys of 150 design practice professionals offer an insight into praxis readiness for Deep Retrofit and a quantitative analysis of cost optimal calculations highlights deficiencies in methodologies, which could undermine the validity of the (Government) recommendations.

The case studies and pilot project in the 'Functional and Process Domain' required both the qualitative and quantitative analysis of unpublished design stage reporting, post occupancy reports, surveys and interviews. Cross case comparative analysis involved content and frequency analysis (Silverman 1993)[122] adopting a 'Grounded Theory' approach and participatory action research. 'Grounded Theory' was used in the context that the content analysis did not prescribe or anticipate the thematic analysis of the coding paradigm. Therefore, the frequency and comparative analysis of themes and codes within the study could unearth unexpected issues, conflicts and challenges, which could be examined and analyzed to generate generalized theories and hypothesis.

The methods employed in the research vary with the different domains and factors being analyzed, however the methods are closely related, contributing to a greater synthesis of facts and findings, allowing this researcher to synthesize and evaluate the various factors that impact client goal setting and design process decision-making in Deep Retrofit.

2.3.4 Debating the suitability of research frameworks and methods

Lawson (1980)[123] believed that design is a complex and sophisticated skill, which could be "analysed, taken apart, developed and practiced". Lawson examined and route mapped the design and architectural processes, "exploring relationships, looking for patterns in the information available" attempting to reveal the power struggles and competing priorities of a negotiated enterprise reliant on multiple internal inputs and external factors. He argued that design practice continues to change and evolve in response to changing requirements and technologies. Lawson expands on the sequences of Markus & Maver (1970) design process, simplifying it into three stages of analysis, synthesis and evaluation, which fold back on themselves (fig 2.2). Lawson saw the singular process of analysis synthesis and evaluation as a cyclical wheel spinning between the problem and solution, rather than a straight line of actions and decisions. Certainly the design process is not a straight line, as Swann (2002)[124] reminds us "the design process is iterative, and reflection is the tool for analyzing design solutions and "synthesizing revised solutions". As such it constantly loops back and firth between synthesis, analysis and evaluation. Like Dewey, Swann, Carr and Kemmis, Jones (1970)[125] (Fig 2.1) identified the identified design process as cyclical, with iterative reflection, analysis, and synthesis.

Where Lawson (1980) maps processes and impart facts, observing the architectural process, and illustrating examples, there is no great overarching methodology that can be harnessed to frame the complexity of the subject at hand. The visualisation and mapping he adopted however have clear potential as methods of imparting findings of the research. Decision-making within the design process, as Lawson (1980) identified can be solution oriented, constrained by the performance goals of the design brief and the parameters of the resources available. Therefore, there are external factors which bear an influence on the formation of the brief and the budget allocated. The brief is not the beginning of the process that influences the design team.

Foqué on the other hand provides a framework for analysis that captures a variety of external domain impacting the design process, thereby better suiting the research of the architectural paradigm based on case study method. The case studies and pilot project examined in this research required comparative (Ragin 2008), and content analysis (Silverman 1993) respectively.

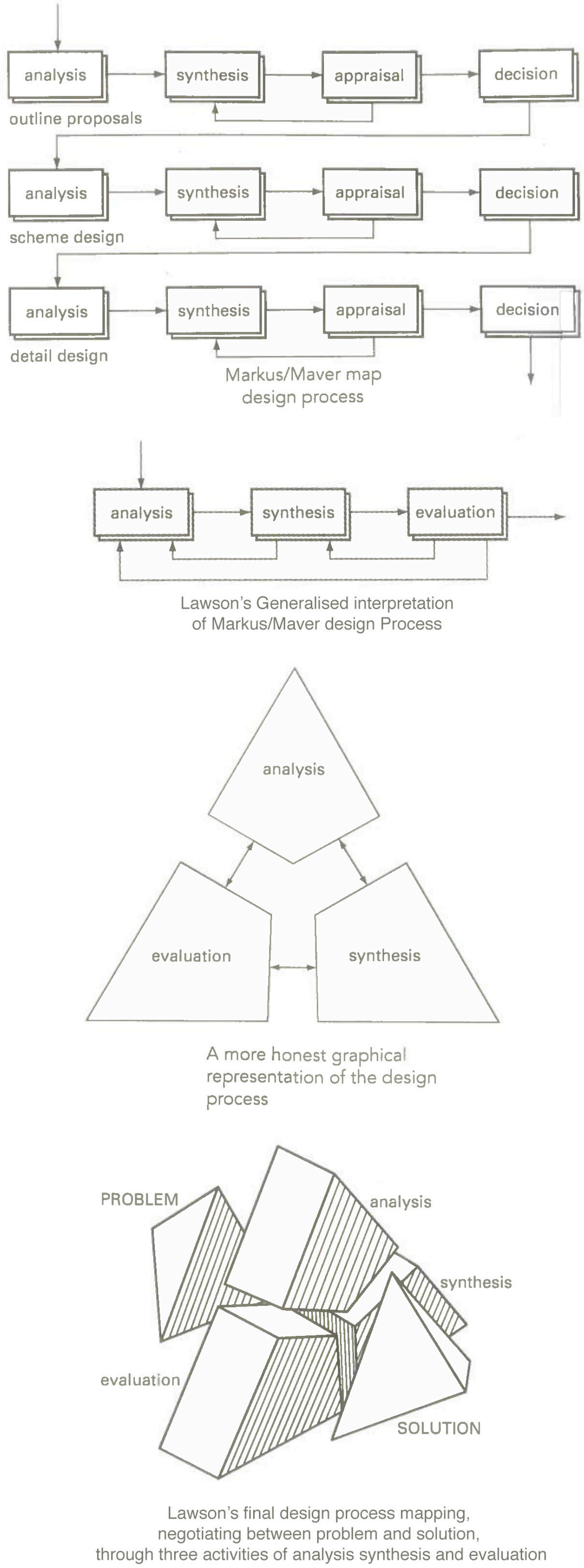


Figure 2.2 Developing the Markus Maver Design Process (Lawson 1970)

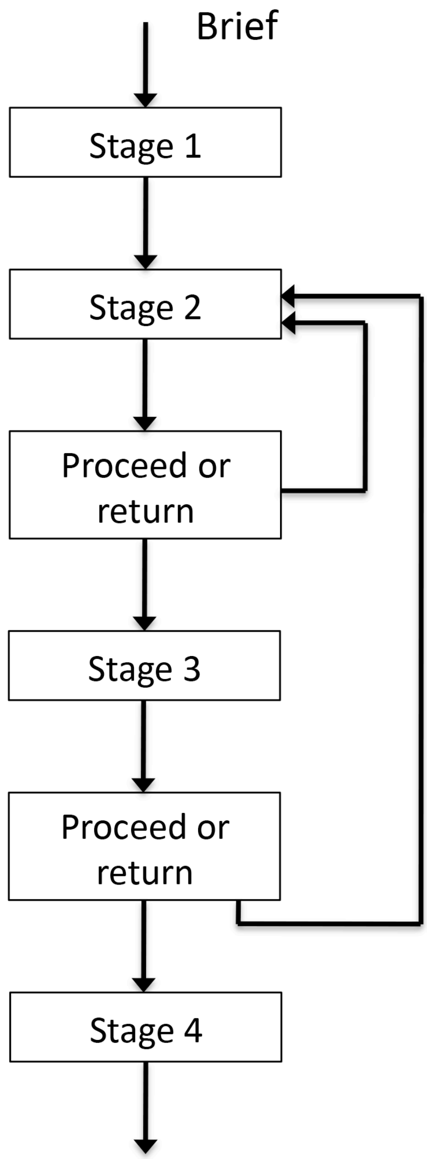


Figure 2.3 Jones Cyclical Design Process (Jones 1970)[126].

2.3.5 Research frameworks and methods adopted

Foqué's Knowledge pocket is adapted to become a framework for mixed method research. The multiple factors, which impacted the design and construction of the original RTCs, are mapped through 'Historical Method' (with a variety of research tools previously discussed). 'Historical Method' is also used to frame the economic and legislative contexts, which inform client decision-making. Case Study Method is adopted to examine 6 RTC retrofits along with a pilot project, using cross case comparative analysis, content and frequency analysis to generate and generalise on barriers to 'Deep Retrofit'. Dialectic Method is used to gain insight from the competing factors that influence the outcomes of Deep Retrofit leading to a Sankey Map of the internal and external factors that impact the Socio Technical System for Deep Retrofit (Ó'Riain 2016) *(Fig 6.12)*. Drawing on Kolb's (1984) cycle of experiential learning, Lawson's route maps of the design process (Fig. 2.2), and Jones (1970) cyclical design process (Fig. 2.3), the research maps decision-making, group dynamics, group activity, faults and gaps in design practices, whilst examining the aspirations, motivations, intentions of stakeholders and the practices of the design team leading to the identification of key systemic and practice barriers to Deep Retrofit, and the development of optimal processes for addressing these barriers.

2.4 Action Research in the Pilot project

As McNiff and Whitehead (2009)[127] note, action research involves reflecting on one's own practice to see how it can be improved and how that knowledge can influence the process.

Participatory Action Research (PAR), relating to an earlier form of participatory research, gained traction in the 1970s (Frideres 1992). Through PAR, Whyte et al. (1989)[128] suggest that the researcher, as a professional expert, could become an active part of the research of a given problem area, influencing its outcomes. Participatory Action Research, as Bilandzic and Venable (2011)[129] refer to it, involves "practitioners as both subjects and co-researchers" (Argyris and Schön 1989)[130]. "The involvement is extensive rather than just consultative, with active participation throughout the research process, from the initial design to the final presentation of results and discussion of their action implications" (Bilandzic and Venable 2011) (Whyte et al. 1989). The participant observer is, therefore, able to elicit greater insight into the process, as they become collaborators in the realisation of the artefact. Carr and Kemmis (1986) found that central to the application of action research was a "self-reflective spiral of cycles (Fig 2.4, 2.5) of planning, acting, observing and reflecting" (Carr and Kemmis 1986)[131].

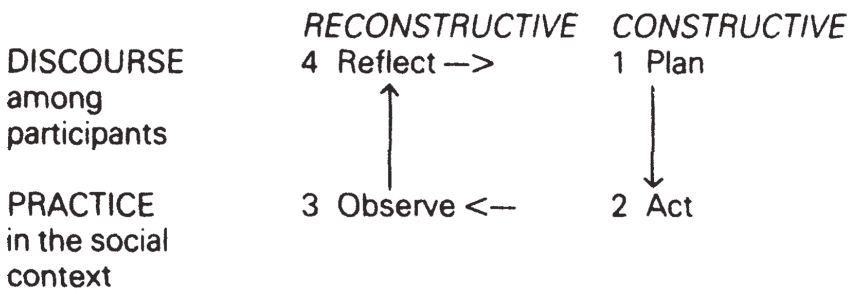


Figure 2.4 Moments of Action Research (Carr and Kemmis 1986)[132].

However, Frideres attacked the potential subjective nature of participatory research: "We have, in the case of participatory research, an inarticulate and illogical set of statements, which reflect little integration and a considerable number of disparate claims" (Frideres 1992)[133]. Frideres' (1992) main issue was with the lack of systematic evaluation of a particular problem set. In responding to this challenge, the participatory action research involved a multidisciplinary team of professional experts, examining the broad range of issues in achieving NZEB performance and their systemic limitations, or barriers, to its diffusion. For the architectural aspect of the research, this was a very suitable and pragmatic approach, as the architectural paradigm tends to be a synthesis of a wide variety of factors.

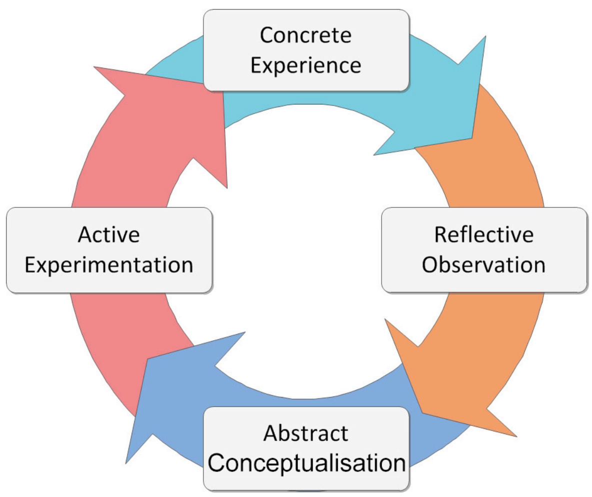


Figure 2.5 Experiential learning cycle model (Kolb)[134].

Domain Stages are mapped in figure 2.1 and for clarity is numbered to reflect the chapters in which they are covered.

2.5 Tools specific to mixed methods

2.5.1 The Formal Domain: Chapter 3, Method and data collection

Chapter 3 explores the parameters that influence the aesthetics, form and performance of the original RTC buildings (1967-1974). The goal of this analysis is to reconstruct the architectural and social context in which the Regional Technical Colleges were designed in 1966/67. This chapter determines how and why these contextual parameters influenced the design decision making and goal setting for the construction of RTCs. This analysis informs both the historical practice of architecture in an Irish context, potential paradigm bias, and the impact of technological development on case study building design (Foqué 2010)[135]. The chapter seeks to identify why the buildings are the way they are, to identify the forces that shape the buildings (Fitch 1972)[136].

To establish first, the historical context, secondary material was critical. A review of texts by and about the following key protagonists significantly informed this stage:

- Muthesius (Muthesius 1994)[137],
- Loos (Loos 1982)[138],
- Gropius (Gropius 1943)[139],
- Corbusier (Corbusier 1931)[140],
- Arup (Arup 1970)[141].

The following authors contextualised the works of seminal architects and authors, framing a background of the Modern Movement, and providing an excellent contemporary reflection on the changes to the architectural paradigm preceding the original RTC design in 1967:

- Banham (Banham 1955)[142],
- Crinson and Zimmerman (Crinson and Zimmerman 2010)[143],

- Grindrod (Grindrod 2013)[144],
- Millais (Millais 2009)[145],
- Jones (Jones 2014)[146],
- Brady (Brady 2000)[147],
- Anker (Anker 2010)[148].

There existed no written history of the design of the Regional Technical Colleges, though some published, unpublished and declassified documents from the design team, the Irish Government and the World Bank were in existence prior to the research. The research unearthed existing primary sources of information from the Institutes of Technology, in the form of drawings, minutes, notes, internal reports and specifications. Similar documentation was sourced from the Department of Education, Parliamentary Library (Dail Library), the Architectural Archive, National Archive, Arup Library (London), Loughborough University, Loughborough town library, the University of Birmingham and the World Bank archives (Washington). Whilst there were a few books that referred to the political background to the establishment of the RTCs, perhaps the most insightful published record informing the nature of the client and his priorities was produced by Magill (Healy 1988)[149].

The specific unpublished reports and government documents, which framed the reported context and process, are listed below:

- Interim Report on Regional Technical College, Cork, O'Flynn Green Architects, Cork (1966), containing information, which informs the RTC performance brief.
- Minister's Steering Committee on Technical Education, 'Report No. 3, Final Preliminary Brief for the Regional Technical Colleges, Part 1 General Report', 1967, containing the RTC performance brief.
- Regional Technical Colleges, Preliminary Report on the progress of the Regional Technical College programme up to October 1968, containing the RTC performance brief and some design details.
- Regional Technical Colleges, Finbarr McSweeney (Arup), IRIS. 1974,

containing design details on Waterford and Cork RTCs.

- Project Performance Audit report (World Bank 1980) containing a post-occupancy evaluation of the original RTC projects.

Further background information on technical construction came from:

- *Technical Colleges and colleges of further education* Price (1959),
- *The Architects Approach to architecture* (Sir Phillip Dowson 1966),
- *Key developments in the History of Concrete constructions* (Addis 2008),
- *Arup Associates* (Brawne 1983).

The legislative context of the creation of the RTCs and their subsequent design is informed through a critical appraisal of OECD reports, Irish government reports, Irish government policy and Parliamentary debates. The reports on *Investment in Education in Ireland*, by the OECD (1962)[150], *Comments on Investment in Education, Report number 16* from the National Industrial Economic Council 1966 (Whittaker 1966)[151] and notes on the *Symposium on Investment in Education* (Cannon 1966)[152] were all critical to informing the political context which would frame the formal aspiration of the RTC designs in 1966/67. Due to the limitation of space, a great deal of this information is reported in the Appendix 3.

Chapter 3 contextualises the architectural process leading to the design of the original RTC buildings, how the design had developed from its precedent, and how it changed thereafter. Brawne's insight as an employee of Arup, together with Ove Arup's *Philosophy of Design* (Arup 2012)[153], his key speeches, the *Master plan for the Loughborough University of Technology* (Arup Associates 1966)[154], the O'Flynn Green report (O'Flynn Green Architects 1966)[155], publications, speeches, and interviews with surviving design team members and stakeholders, all help inform the pattern language, decision-making, priorities and technologies employed to shape the RTC buildings between 1966-1974.

Interviews with the original surviving design team members and site visits to both Loughborough (Arup Associates 1966), and Birmingham University (Brawne 1983)[156] buildings helped identify the key typological link to the precedent design for the RTCs. The discovery of the Government preliminary report (Department of Education 1968)[157], an internal Arup article called *Iris* (McSweeney 1974)[158] and a Building Design Associates Brochure (BDA, 1970)[159] at the National Architectural Archive, helped identify the key personnel in the design teams, as well as the original structure and the potential for a third floor.

The design team and stakeholder relationships are reconstructed from primary investigations and interviews. Key surviving personnel involved in the design and client design process from 1967-74 were interviewed to establish the relationships, continuity and discontinuity of the design process. This offered insight into the influence of key factors on project outcomes and attitudes towards energy in buildings prior to the oil crisis in 1973. As the design and project teams varied across the country it was possible to identify the key design teams but not to find all the individual stakeholders, as much time had passed and some people are no longer with us.

It was however, possible to find and interview key personnel in the original BDA design team (McSweeney and Burgess), the original project team at Cork RTC (Kelly and McCarthy) and an original client team member (Pollard 2010)[160], after much investigative work. Although the "Irish Life and Lore Series" from the Cork Institute of Technology identified key original college personnel, the information therein did not contribute to the research topic. The interview with McSweeney (McSweeney 2014)[161] and Burgess (Burgess 2014)[162] were key to informing new knowledge on the formation of BDA (the original design team for the RTCs) and the key motivations informing the design and its artefacts. The findings from these interviews were supporting by evidence from multiple separate streams of information, including Dáil (Parliamentary) speeches, to a Magill Magazine article (Healy 1988)[163] and the later discovery of a BDA brochure (BDA 1970)[164] at the Irish Architectural Archive. Arup Library in London and Archiseek were also both very helpful in discovering new and relevant sources of information on the key protagonists.

The first description of the RTC typology was first established by the Government Preliminary Report (1968) and then supported by McSweeney's (McSweeney 1974)[165] internal Arup report in 1974, together with site inspections and site visits, initially to Cork, Waterford, Carlow, Dundalk Galway, Sligo, Athlone and Letterkenny, where some original drawings and specifications were found.

Interviews with Burgess (BDA architect)[1] and McSweeney (Arup engineer)[2] on the original RTC template design for Waterford identified the key premise and link to Arup Associates Birmingham/Loughborough buildings.

A Stanford report (Stanford School Planning Lab 1962)[166] on British Prefabricated School construction established concurrent UK building costs, whilst the declassified World Bank report (World Bank Operations Evaluation Department 1980)[167] established the RTC building costs in an Irish context, allowing for a direct comparison.

The historical record arising from this work is new and original, representing an untold story. It was published in an industry article (Ó Riain 2015)[168] and in a peer reviewed publication (Ó Riain 2015)[169].

In summary, Chapter 3 addresses the *Formal Domain (also referred to as domain stage 3)*. It reconstructs, from primary and secondary sources, the formal and technological aspects of the original artefact, linking it to its precedents; in essence, establishing the representative nature of the

[1] *Burgess Interview in appendix 3.1*
[2] *McSweeney Interview in appendix 3.2*

typology within its temporal and architectural contexts.

2.5.2 The Contextual Domain: Chapter 4: Methodological approach and data collection

In examining the published literature, Chapter 4 summarises the process stages from the *Contextual Domain (Stage 4)*, mapping the relationship between rising public awareness of environmental issues and their societal/political response. The domain attempts to place the original RTC design at a pivotal point in time where the oil crisis (1973/74) influences the geo-political and socio-economic spheres. As cold war politics and trans-national pollution changed global priorities, the chapter questions which factor had the greater legislative response and impact on low energy building design. All of this stage is based on secondary sources.

The *Contextual Domain* is examined through the geo-political energy crisis, the expedient political response that led to the establishment of the International Energy Agency (IEA), changes in building energy regulation and the prioritisation of low-energy building research. The chapter begins to link to the *Normative Domain*, by mapping key developments in low-energy building design and how they interplay with economics and policy, leading in some cases to national legislative standards for building energy performance. The varying influence and changing priorities of politics and economics on the development of low-energy design are mapped, illustrating the close relationship between oil price, national legislative action and emergent low-energy building practices.

Reports from the OECD (Scott 1994)[170], IEA (Scott 1994)[171] and US Foreign Relations Committee (US Foreign Relations Committee 1974)[172] highlight the legislative response to the first oil crisis. Secondary sources informed a reflection on the development of environmental awareness in building and the policy reactions to the first oil crisis. Journal papers by Korsgaard and Esbensen (1977)[173], Schick, Jones and Harris (1979)[174], Steinmüller (1979)[175] and Najafi (2011)[176] were used to map the development of low-energy buildings, noting early exemplars of technologies, strategies, and processes that framed current practice and its legislation. Other publications, such as patents, in-filled some interesting developments in the US, from solar housing to Bentley's (1976)[177] double-wall house to the Princeton House Doctors (Socolow 1991)[178].

The US report from the Foreign Relations Committee (1974) is critical to understanding subsequent international policy on energy security. Much of today's energy security policicies from the US can be linked back to this document (Ruester 2016)[179]. The academic papers on Denmark's *Zero Energy House (1975)*, *The Lo-Cal House (1976)*, *Saskatchewan House (1979)* and *Twin Rivers (1978/79)* retrofits would appear to be the basis of the development of the *Passive House* standard (1988) and very important to the basis of best practice today in low-energy buildings.

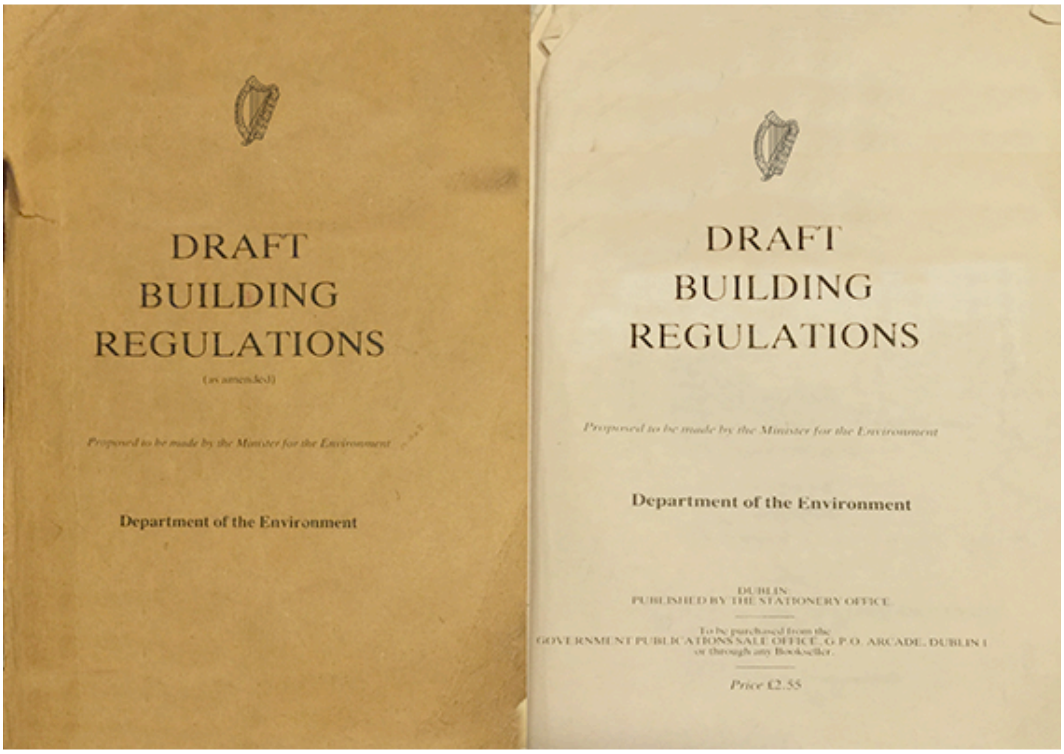


Figure 2.1 Irish Draft Building Regulations (The Department of the Environment 1976)[180]

Original published Draft Building Regulations in 1976 contextualises the Irish legislative response to the oil crisis, with US Department of Energy online resources mapping US policy changes and the changing environmental priorities, as political parties switched power. Parisi (1977) highlighted the contemporaneous conflicts between energy policy and environmental policy. Various international agreements and the observations of authors like Bošnjaković (2011)[181] and Scheuer (2014)[182] contextualised the rise of environmentalism in geopolitics around the fall of the USSR, Chernobyl and up to the first Kyoto Protocol.

In summary, Chapter 4 partially addresses the *Contextual Domain*, linking topics to the *Normative Domain*. It frames the original building in its temporal position, informed by a review of secondary sources, highlighting the changing priority towards greater energy conservation in buildings after the oil crisis and the reasons for the demise of energy conservation design strategies in the 1980s.

2.5.3 The Normative Domain: Chapter 5

Methodological approach and data collection

The following key elements are addressed at Chapter 5, the *Normative Domain*:

- Cost-optimal,
- Operational cost,
- Budget
- Building standards,
- Legislation,
- Existing building lifespan,
- Net present value.

The stage also refers to the *Functional/Process Domain* as it addresses the use of building performance simulation and scenario analysis. The majority of the stage includes a review of secondary sources such as EU directives, national legislations, national policy and national transposition reports. This leads to comparisons that are supported by primary sources such as interviews and surveys.

The chapter maps some key legislative changes that arise from the Energy Performance Directive 2002 (EPD 2002) to the adoption of *Building Energy Rating* and *Energy Performance Certificates* through the transposition of the EU Directives into national laws, reports, guidance and regulations. The study elicits a growing story of non-compliance, both from industry articles and research studies. Secondary publications were examined along with contemporary reports that support the contention that there was a growing level of non-compliance with building energy regulation in Ireland and the UK (2005-2011). Important contributions from some key authors frame the context of non-compliance: Attia highlights a low level of building performance simulation usage by architects, Pan and Garmston attribute compliance difficulties to lack of practice knowledge, with Cox highlighting poor awareness of thermal bridging as a key issue in non-compliance.

The stage introduces a survey of 150 design practitioners (Appendix 5.1) to "estimate with reasonable precision" (Dillman 2011)[183] the adoption of energy performance simulation software by architects compared to engineers, and establishes practice readiness for NZEB. Nesbary (2000)[184] argued that surveys could be used to establish a "representative sample data from a larger population and using the sample to infer attributes of the population". The survey is used to support Attia's contention that engineers more frequently used BPS tools than architects. Participants were invited to an online questionnaire using LinkedIn contacts, emails, discussion lists and personal contacts.

A variety of sources from National and EU Regulations (EUROPA 2002)[185] and the Sustainability Energy Authority of Ireland (SEAI 2008)[186], to industry magazines like Construct Ireland (Colley 2011)[187] and Passive House Plus (Antonelli 2012)[188] (who have written extensively on energy and regulation subjects), Fraunhofer (Fraunhofer 2009)[189] and Ecofys (ECOFYS and Fraunhofer 2010)[190] (who are pre-eminent sources for European energy in building research), papers by Schleich and Gruber

(2008)[191], Menezes (2012)[192], De Wilde (2014)[193], Leaman and Bordass (2014) [194], Graffy, Lidstone and Roberts (2008)[195] all contextualise the legislative efforts with Kyoto and COP 21 emission abatement targets, architectural praxis and knowledge gaps of low-energy building retrofit.

Chapter 5 completes with a review of the proposed Irish cost-optimal targets for NZEB. The inception and principles that advanced the EPBD cost-optimal regulations and guidance informed by Aggerholm (2011)[196], Boermans, Hermelink and Schimschar (2011)[197] were examined in the context of Irish and UK transposition calculations. The reporting structure and methodology of the regulations and guidance were examined through Kurnitski et al. (2011)[198] and Ascione et al. (2015)[199], followed by an examination of the regulation itself (European Commission 2012)[200]. The research examined the national transposition reports, which followed the EU guidance by the UK (AECOM 2013)[201] and Ireland (AECOM 2013 and AECOM 2015)[202,203] between 2013 and 2015, reporting on compliance to methodologies, reference selection and commenting on the potential impact of the reports recommendations on design practices and the potential to achieve a wider market adoption of NZEB retrofit.

In summary, Chapter 5 addresses the *Normative Domain* comparing policy intensity and diffusion to emission targets, and the potential for retrofit regulations to drive market demand for *Deep Retrofit*.

2.5.4 The Process Domain: Chapter 6

Methodological approach and data collection

The *Process Domain* is addressed in Chapter 6 through a series of case studies. The case studies allowed the researcher to also question the process of decision-making, relating this to operational energy saving. Therefore, the case studies also reference aspects of the *Formal* and *Normative Domains* in discussing and analysing the use of scenario analysis in client goal setting and design stage decision-making. The *Functional domain* is referred to in the context of post occupancy evaluation where that exists. However, the main section of the *Functional domain is addressed in Chapter 6 and Chapter 7.*

The integration of "technological knowledge and artistic interpretation" (Foqué 1999) [204] is embodied in the design product. Where change is the steady state of practice changes to the RTCs over time contextualise the multivariate priorities of stakeholders, demonstrating both technological and contextual responses to retort. The stage presents comparative cross-case research studies of architectural solutions and related decision-making, in the planning and realisation of RTC retrofits over a 13-year period (1998-2011). Case-based research is the cornerstone of the reflective practice (Schön 1982)[205], thus this stage used RTC retrofits as case studies to understand how stakeholder priority and relational networks change as a result of external and internal forces.

The primary research involved a detailed search of original construction drawings and specifications from 1968, unpublished design stage proposals for retrofits, a detailed survey of the existing case study building to record and resolve design variations, reporting on intervention strategies, interviews with the original architect, engineers, local stakeholders and current building operators together with the simulation modelling of details. Cross case comparative analysis helps establish the key barriers to deep retrofit in Ireland across a series of retrofit case studies. In addressing these barriers an outline socio technical process for deep retrofit is developed. This "Outline Process is tested through a pilot-project reported in chapter 7.

2.5.5 The Functional Domain: Chapter 7

Methodological approach and data collection

A Participatory Action Research methodology was adopted for Chapter 7, the *Functional Domain*. The initial part of the chapter examines seminal research in low energy design processes to inform the "outline socio technical design process". The rest of the chapter reports on two pilot projects, which test the "outline- process" and compare outcomes with and without process supports.

The chapter includes a summary of Phase 1 retrofit of the case study building at Cork Institute of Technology, involving research of some internal unpublished reporting of energy consumption, plus data from BMS databases at Cork Institute of Technology. Other unpublished data includes meeting minutes, internal reports, design team reports, tender documents and specifications. Primary research included the test phase of the pilot-project, surveys, simulations, inspections, photographs, blogs, research journal, website, interviews, surveys and other measurements. The pilot-project, which followed 8 reflective participatory action research cycles (Graph 2.8), was measured through post occupancy analysis by Engineering researcher 3 (and reported in this chapter). Content and Frequency analysis was used to analyse design team communications to elicit further barriers to deep retrofit.

Phase 1 was an action in a 'concrete phenomenalism' or operation (Piaget 1970)[206]. Bilandzic et al. (2011)[207] refer to "practitioners as both subjects and co-researchers" (Argyris and Schön 1989)[208]. The researcher's aim was to broaden knowledge of low-energy retort, reflecting Stage 1 of Piaget's model for learning and cognitive development at the initial enactive stage, which is the starting point for action research. This model of 'action research' encourages researchers to experiment through intervention and to reflect on the effects of their intervention and the implication of their theories"[209] (Avison et al. 1999).

Brown and Jones (2011)[210] questioned both the objectivity and the consistency of the researcher and the world during the process of the action research. Whilst in PAR, researchers reject the notion of neutrality in action research (O'Brien 2011)[211]; the issue of scientific objectivity is still in question. "Objectivist forms of knowledge require a person to distance themselves from their own capacity for self-knowledge" (McNiff

2011)[212]. McNiff proposes that action research allows the researcher to reflect on one's own practice, to see how it can be improved. The Phase 1 action research aimed to establish learning outcomes for architectural practice and the design process for Deep NZEB retrofit and establish the potential to achieve NZEB performance through Deep Retrofit in Ireland for the first time. The architectural component is examined and analysed within the context of the wider design team, where the design team are supported by a research team interaction following the 'outline socio technical design process'. "'Objectivity', therefore, is achieved when participants reveal a willingness to make their views and preconceptions available for critical inspection and to engage in discussion and argument that is open and impartial" (Kemmis 1986). Phase 1 decision-making was broken down into nine stages of reflections (Graph 2.3).

Graph 2.3 Zero2020 Pilot-project Participatory Action Research process applied in Chapter 7 (Ó'Riain 2016).

Method

A multidisciplinary research team (including the author, hereafter referred to as the *Architectural Researcher*) at Cork Institute of Technology (CIT) met in October 2010, and challenged themselves to realise an NZEB retrofit performance, in a Cork IT (formerly RTC 1974) building, to act both as a test bed for low-energy building research and a pilot-project for the NZEB retrofit of the remaining 26,750m^2 building. Their intent was to work as a collaborative research team (1 architect, 1 mechanical engineer and 1 building services engineer) following the 'Outline' Socio Technical Process for Deep Retrofit to:

- Define the existing baseline building performance,
- Establish the main reasons for energy demand,
- Examine precedent low-energy strategies,
- Identify appropriate NZEB retrofit energy conservation measures,
- Establish client goals in line with EPBD 2010 aspirations
- Simulate pre-design stage energy performance,
- Secure funding,
- Appoint a design team,
- Monitor and observe the design team process,
- Augment design process where necessary, to realise an NZEB performance,
- Monitor the construction stage,
- Measure building energy and environmental performance over a year,
- Report on results.
- Amend or improve 'Outline' Socio Technical Process for Deep Retrofit

The specific roles and research interests of all participants are outlined in Ch. 2.7 and 7.5.3.

The research team developed a proposed NZEB strategy and building performance brief. This formed the basis of a tender for the appointment of an external design team. The design team developed an architectural response to research strategies, realising an artefact in May 2012. The role of the researchers, after the appointment of a design team, was to act as a collaborative resource, providing reflexive and dialectical critique (Brien 2011)[213], reflecting on the values and priorities we place on inputs and the seminal factors that influence or drive design team decision-making. The researchers help validate the performance implications of various design decisions, and suggest performance related design interventions, within the common constraints of budget and time.

The project was recorded from its initiation in November 2010, to its realisation in May 2012, through to its monitoring and performance results stage in September 2013. Communications and notes were logged and records were kept on a daily basis, recording progress, observations and insights (Appendix 7.1). A video log recorded the build stage and a photographic log recorded the build on a daily basis. A concurrent research project website (Zero2020energy.com) was created for dissemination (with 3484 unique visits) (Ó Riain 2012)[214]. The building had environmental sensors installed to monitor temperature and humidity. Plug load monitors recorded the extent of non-regulated loads post occupancy. The Building Management System (BMS) software could record the energy demand from each room and service separately. Lighting, heating, plug loads, temperature, carbon dioxide concentrations could all be recorded and reported separately. Behavioural sign-in sheets recorded the opening and closing of manual ventilation louvers. The building services engineer was trained on the BMS system and he reported on the annual performance in 2014 (Delaney 2014)[215,216].

The action research project was recorded initially through meeting minutes, and then through a reflective daily journal, recording notes, emails, communications, actions and decisions. Quantitative simulation analysis, energy analysis, designs, drawings and specifications were recorded as reports in appendix 7 and commented on in the text. Field observations, simulations and recording demarcation were divided amongst the three researchers. The qualitative data was then analysed using content and frequency analysis (Silverman 1993)[217], to unearth unexpected issues, conflicts and challenges to generate generalized theories and hypothesis (Ch 2.33). The findings from the chapter support modifications to the 'Outline Socio Technical Process for Deep Retrofit (Fig 7.14).

2.5.6 Chapter 8

The final stage (Chapter 8) provides a synthesis and discussion of the conclusions from product, context and process (PCP) analysis, covering chapters 3-7. It outlines how various factors influence low-energy building design in an Irish context, reporting on key findings from the PCP analysis, surveys, case studies and pilot-project. The outcomes from the various strands inform findings both on the technical challenge of achieving NZEB performance through retrofit and the systemic challenge of market demand for low-energy design. Results are interpreted and research questions are addressed. Chapter 8 addresses the research questions and discusses their implications of the findings for NZEB policy and market adoption of NZEB retrofit in Ireland.

2.6 Research Problems and limitations

The research topic was limited to the retrofit of non-domestic buildings. The research study was very wide: it required separate data collection methods for each domain stage. As a result, the research was not overly deep in specific areas. It does however, synthesise the totality of problem areas.

As the case study RTC building original design dated from 1967, many of the original stakeholders have passed away, yet it was possible to identify, locate and interview living members of the original design teams at various locations. There was a lack of published written record - most of the records relating to the original RTC building and the subsequent case study retrofits were very dispersed. They included, for the most part, internal reports, classified government departmental documents and reports, user manuals, drawings, specifications and photographs. This resulted in a high degree of field research, interviews, surveys, simulation, and general detective work to identify and record rich sources of original data. It was however, possible to visit and survey each RTC building in Ireland, as well as case study buildings at Birmingham and Loughborough Universities. There was a considerable level of cooperation from each college and many interviewees gave their time willingly.

2.7 Demarcation of research roles (also see 7.5.3)

The participatory action research project involved a number of researchers and stakeholder participants over a period of 3 years. The research areas of the three research protagonists were different, but with similar low-energy performance goals. The architectural researcher was primarily interested in the context and physical attributes of the original RTC design, surveying precedents, establishing the commonality of the typology, and the detail of its existing construction. The architectural researcher was also interested in:

- How precedents could inform an NZEB retrofit strategy,
- The barriers to NZEB retrofit adoption
- Interdisciplinary design solutions
- The potential to achieve NZEB retrofit through passive means,
- The process of how that was achieved,
- Using simulation modelling (using Therm and WuFI) through a reflective process for energy performance validation,
- Façade performance validation (Hygroscopic and Thermal transfer),
- Surveying,
- Observing and recording the design and construction process,
- Validating that the building was constructed to the performance specifications,
- Analysing the outcomes and proposing improved design processes
- Disseminating findings.

The mechanical researcher was concerned with establishing existing energy performance using TRNSYS (Transient Systems Simulation Program)[3], natural ventilation, air movement, buoyancy and indoor air quality (IAQ) and louver design. The building services engineer's interest was in active systems, monitoring environmental conditions, PV renewable installation, BMS, ASHP, thermal comfort, and measuring and reporting on post-occupancy energy performance. All three researchers worked in a collaborative manner establishing a design strategy, fundraising, and reflecting on design team decisions to realise the project. A collaborative paper was published after the project was completed and this thesis refers to that paper and some internal reporting. The architectural researcher collaborated with engineering researchers for reporting on post-occupancy performance, and depends on the validity of the collected and reported data findings from BMS monitoring systems.

The following chapter 3 introduces the historical context to the formal domain with architecture, examining the key factors that influenced the design of the original RTCs and priorities that inform the architectural paradigm. The key precedents and seminal influences of budget, technology and client goal setting on design team decision-making for the original RTC design are mapped. The construction and commonality of the RTC typologies are explored to inform their suitability for retrofit.

[3] TRNSYS (Transient Systems Simulation Program) was originally developed in 1975 and was also known as TRANSYS, but the computer code it is based on FORTRAN only allows for 6 characters, therfore TRANSYS became TRNSYS (Löf 1993).

CHAPTER 3

A CONTEXTUAL ANALYSIS OF THE FORCES THAT SHAPED THE DESIGN AND CONSTRUCTION OF THE REGIONAL TECHNICAL COLLEGES

Chapter 3: A contextual analysis of the forces that shaped the design and construction of Regional Technical Colleges

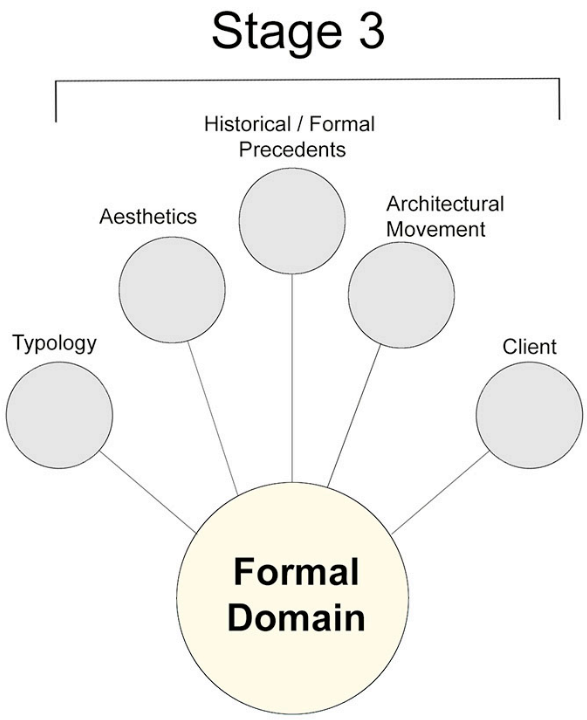
3.1 Methodological Statement

Following Foqué's *Product Context Process* analysis (PCP), the goal of this research stage was to examine the *Formal Domain* (Graph 3.1), mapping the circumstances or factors that influenced the existing Irish Regional Technical College (RTC) building design in 1966/67, including architectural movements, precedent, aesthetics and construction. This chapter determines how and why these contextual parameters influenced the design and building decisions, unveiling, mapping and understanding the relational network linking the different contextual components of society, politics, economics, architectural theory, style, technology and precedent, in advance of the actual design period (Foqué 2010)[218]. The product, or artefact, engenders the 'building genome', composing the data that reflects the design process, its *Functional, Formal* and *Contextual Domains*. Therefore, the establishment of an artefact's context can help explain the influence on the design process, eliciting facts about the buildings design and construction.

Context analysis examines the interplay of architectural influences, politics, design team participants, and precedent practice, unravelling the relational networks, points of continuity and discontinuity in the creation, form and performance of the original design of the RTC buildings 1969-1974.

To establish first the historical context, secondary material was critical. The following is a list of key protagonists whose work contributed significantly to the first half of this stage:

- Davies & Weeks (1951)[219]
- Dawson, P.M. (1966)[220]
- Arup (Arup 1970)[221].



Graph. 3.1 Structure of the *Formal Domain.*

The following authors contextualised the works of seminal architects and authors, framing a background of the Modern Movement, and providing an excellent reflection on the changes to the architectural paradigm preceding the original RTC design in 1967:

- Banham (Banham 1955)[222],
- Crinson and Zimmerman (Crinson and Zimmerman 2010)[223],
- Grindrod (Grindrod 2013)[224],
- Millais (Millais 2009)[225],
- Jones (Jones 2014)[226],
- Brady (Brady 2000)[227],
- Anker (Anker 2010)[228].

Process Analyses

This chapter also seeks to gain as much insight as possible into the pathology of the building and the elements that became priorities in the process. The process analysis explores evidence from the following primary (unpublished) sources:

- Unpublished and declassified secondary sources (World Bank Operations Evaluation Department 1980[229]), (Mulcahy 1967[230]),
- O'Flynn Green Regional College Cork Report (O'Flynn Green Architects 1966)[231],
- The steering committee preliminary brief (Department of Education 1967)[232],
- Unpublished departmental preliminary reports (Department of Education 1968)[233],
- A subsequent Arup internal report (McSweeney 1974)[234], (Kelly 2010)[235],
- Interviews from those involved in Building Design Associates (BDA) (Burgess 2014)[236], (McSweeney 2014)[237],
- Interviews from those involved in Cork RTC Construction (McSweeney 2014)[238], (Kelly 2010)[239], (Pollard 2010)[240], (McCarthy, 2011)[241],
- Parliamentary Questions on the subject of Regional Technical Colleges (1965-1969).

This stage compared "information from the multiple stakeholders with the same story to transform subjective interpretation and believed truth into contextual objective facts" (Foqué 2010)[242]. The research is examined on three levels: decision-making, relational networks and continuity.

Product analysis mapped "several constituents" of the RTC original design, primarily focused on the physical attributes of the original design. The product was analysed on 5 different levels:

- Functional,
- Morphological,
- Technical,
- Environmental,
- Cost.

This is followed by a discussion on the interaction of the 5 parts as an integrated architectural artefact. The Materials and Metallurgy (M&M) building at the University of Birmingham (1965) and Loughborough University (1966) by Sir Phillip Dowson are examined as direct typological precedents to the RTC design. The precedents offer a similar approach to similar functional use in a similar temporal context, with different praxis knowledge, experience and client priorities. The architectural problem approached by Arup Associates gave rise to different and unique solutions in the same spatial and time context. The product analysis also records and represents the characteristics of the original design from multiple sources.

The product analysis explores evidence from primary and secondary sources such as:

- *Master plan for the Loughborough University of Technology* (Arup Associates 1966)[243],
- Key speech by Ove Arup (Arup 1970)[244],
- BDA Brochure (BDA 1970)[245],
- Site visits to both Loughborough and Birmingham Universities (Ó Riain 2013),
- A talk by Sir Philip Dowson after he had completed the two universities: *The Architect's approach to Architecture* (Dowson 1966)[246],
- A book on Arup Associates (Brawne 1983)[247],
- Interview by Sir Phillip Dowson (Associate Architects 2009)[248],
- Original unpublished Drawings and Specifications (from Carlow, Dundalk, Waterford, Cork),
- *Key developments in the History of Concrete constructions* (Addis 2008)[249].

The *Formal Domain* reconstructs, from primary and secondary sources, the formal and technological aspects of the original artefact, linking it to its precedents. In essence, establishing the representative nature of the typology within its temporal and architectural contexts.

3.2 Introduction

The *Formal Domain* charts the early development of environmental thinking in architecture, up to the radical paradigm shift of Modernism and Brutalism. The resulting emphasis on proportional grammar, over the technical performance of the interior environment, would be a recurring theme in educational architecture, leading up to the design of the Regional Technical Colleges (RTCs) in 1967. The key precedent of the RTC design (1967) was the M&M building at the University of Birmingham (1965) and Loughborough University (1966). The intelligence of the building design by Arup would be compromised by the Modernist emphasis on the *pure plastic expression (Mondrian 1993)*[250] of over-glazed façades, which lacked shading and suffered from great heat loss. The movement away from quality materiality and exposed grid structure resulted in a loss of delight and a greater level of brutalism.

The opening of Ireland to international trade in the 1960s saw a projected shortage of 10,000 technicians by 1970, resulting in the creation of Regional Technical Colleges in 1967 (Healy 1988[251], Browne 2008[252]). The pre-oil crisis design of the RTC, and its precedents, resulted in poor energy performance. The large ratio of single-glazed façades and exposed, un-insulated concrete soffits and cladding all lost heat quickly in winter and overheated in summer. This would be highlighted after the spike in oil prices in the winter of 1973/74. "The structure and design of the building has created many problems, such as heating. As the building is not insulated, heat disappears quickly. The expanse of glass and bare block walls add to the coldness of the structure which is ugly to the eye" (Mills 1974)[253]. Political interference, a lack of systemised construction experience and materiality cutbacks resulted in cold, ugly buildings (Mills 1974) that were both uninspiring and costly to run.

As Institutes of Technology (IoTs) (formerly RTCs) move to become Universities, the *Formal Domain* sets out the forces of architecture, education, economics, precedent, politics, philosophy, society and the professional power struggle that shaped their design and their consequential environmental performance.

3.3 The Regional Technical College Design Template

By 1963 Arup Associates was formed in Britain, with architects working collaboratively with structural and service engineers under one roof, developing the principles of Gropius' Total Architecture. Their first project was the Mining and Metallurgy Building at the University of Birmingham 1963-65. Philip Dowson developed ideas for science buildings over a few years, paying particular attention to adaptability and servicing. The project was designed around five interlinked pavilions as 'space defining' rather than 'object'. Each pavilion was based structurally on a tartan grid with extensive prefabrication of concrete elements. "Concrete was the ideal material with which to achieve this integration, since it can easily serve both load bearing functions and interpenetrating voids that are necessary to pass services horizontally through the floor structure and vertically through risers that can usually serve as sheer walls for the building" (Addis and Bussell 2008)[254]. The vertical service risers, which occupy the over-check in the grid, have vent grilles at every floor level, terminating in a weathered chimney at roof level, acting as early stack ventilation. A very narrow (100mm) tinted and unsealed double-skin glazed façade vents warm air from the cavity to mitigate solar gain.

The project was completed in 1965 and went on to win plaudits for its clarity, logic and elegance, winning the 1966 RIBA Architecture Award for the West Midlands (Royal Academy of Arts 2014). Much like City of Refuge (1933) it began to address environmental concepts that would not be fully developed until the 1980s.

The M&M building is the key precedent that would influence the RTCs in Ireland. Arup, consultant engineers, were common to both projects, and the fast track nature of the RTC project forced the design team to look for well-developed precedents. A research team from Dublin travelled to

Birmingham and Loughborough in February 1967, led by the UK Department of Education (Department of Education 1967) to examine the Arup buildings. The concrete tartan grid of the RTCs can be directly compared to the M&M building, with modifications to the over-check of the columns. The servicing strategy is broadly similar, but the external façade is very different. The UK government were very experienced at delivering large multi-site modular constructions since the post-war rebuilding period; however, the Irish government was not.

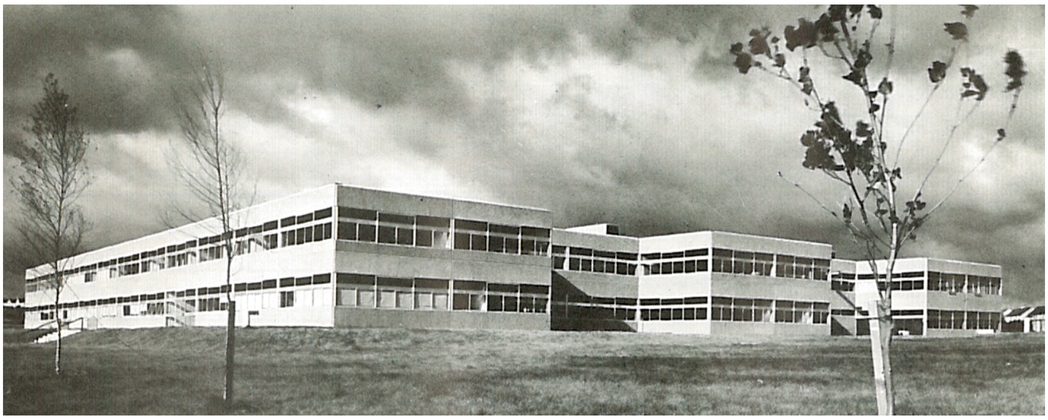


Fig. 3.11 RTC Waterford (1970)

3.4 Linking Loughborough and Birmingham precedents to Irish RTC Designs

A design team for the RTC project (including Ove Arup Partnership) was appointed in late 1966, by the then Minister for Education, Donogh O'Malley. The design team had no brief, as a concurrent *Steering Committee* had been set up to establish the brief. The design team, delimited from travelling to IIT in Chicago, travelled to the Department of Education in London in February 1967, followed by a meeting with Arup Associates (AA). They then travelled to see the most recent relevant AA projects at Birmingham (Dowson 1965) and Loughborough (Foggio 1966). BDA architect, John Burgess (2014)[255] and BDA engineer, Finbarr McSweeney (2014)[256], both recognised and indicated that Loughborough influenced the design of the first RTC project at Waterford (Fig. 3.11). "The design for Waterford developed first and the others were copied from it………. (Burgess 2014)[257].

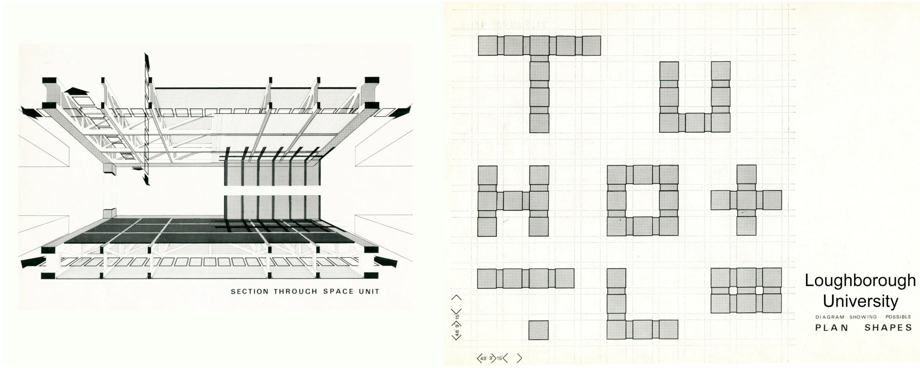


Fig. 3.12 Loughborough University structure and master planning (Arup Associates 1966)

AA had published a book (Arup Associates 1966)[258] and a paper (Thomas 1967)[259] on the Loughborough master planning and the structural/service-based approach planning in 1966, which would have been available to the BDA team. BDA decided to adopt the pre-cast reinforced concrete frame, column structure, tartan grid and 24-foot module (which was a direct descendant of the Hertfordshire models) for the RTCs, combined with an external prefabricated concrete cladding system. Developing from the Hertfordshire precedents, BDA found the 24-foot module as an optimal depth for light penetration; all 7 original designs (Fig. 3.13) are two tables wide (48 foot). It is only at the last project, in Cork, where we see a three-table width, allowing for lecture rooms either side of a corridor (roof lights are introduced to allow more light into deeper spaces).

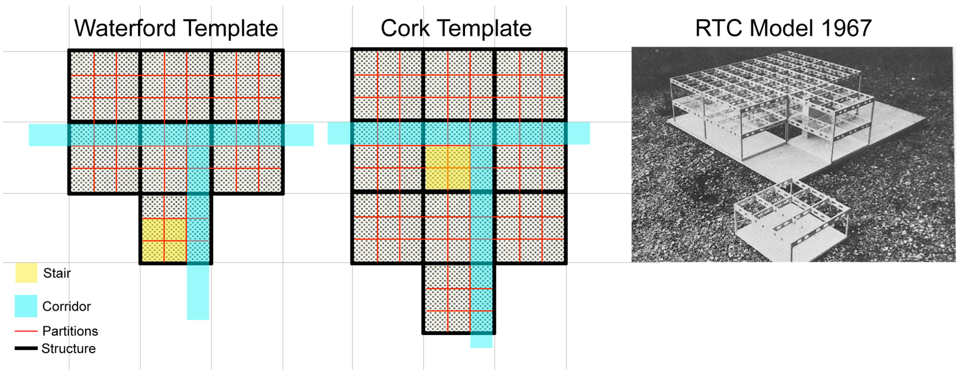


Fig. 3.13 RTC structure and master planning (Ó Riain 2016) and (Arup 1974)

There are some other critical variations in the RTC design, from its precedents at Loughborough and Birmingham. The RTC design envisaged expansion primarily along the length and not the width. The original RTC design omitted the service riser (cross-check column layout), instead casting individual table units together. The RTC buildings, unlike Birmingham and Loughborough, are positioned on their sites, not for view or light, but for longitudinal expansion (Fig. 3.17). Tables are clustered into T-Units (Fig. 3.13) (including seven 2 two storey table units) for planning. If we examine figure 3.13 we can easily identify the T-Units in the Waterford RTC plan (Fig. 3.16).

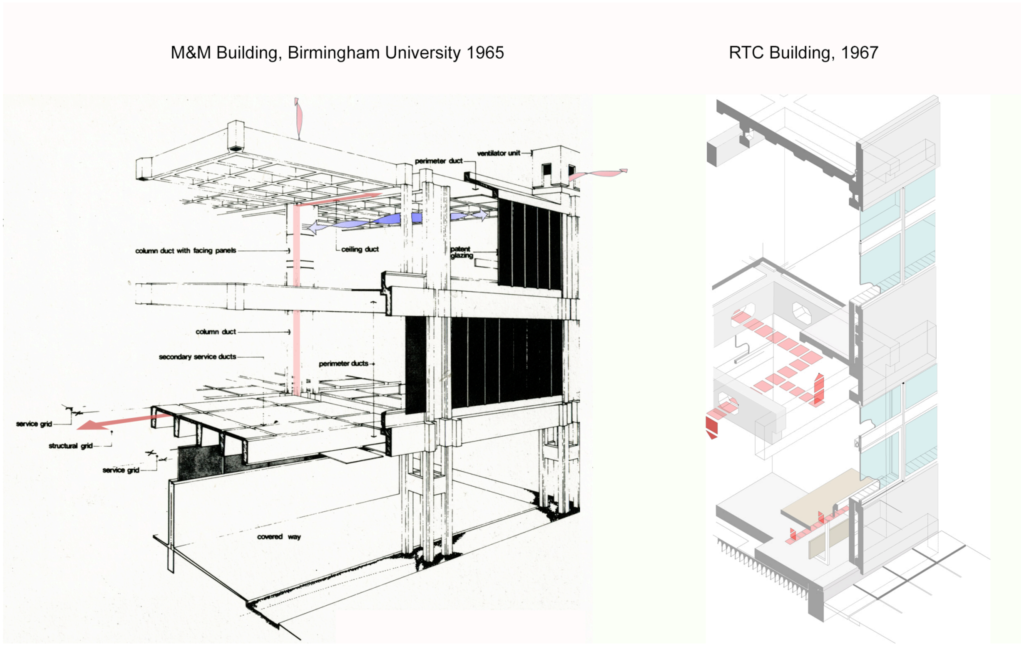


Fig. 3.14 RTC structure and master planning
(Arup 1974-left & O'Riain 2012-right)

The original RTC design located the stair in the linking leg of the T plan unit, differing from the Birmingham precedent. In the final RTC project (Cork), the stair was located in a very similar, central position to the Birmingham precedent. "People move to the light" argued Dowson (2012), commenting on the use of phototropism in the centrally located stair (at the original M&M Birmingham building 1965)[260].

3.5 The Formal Domain: Composition, tectonics, and texture

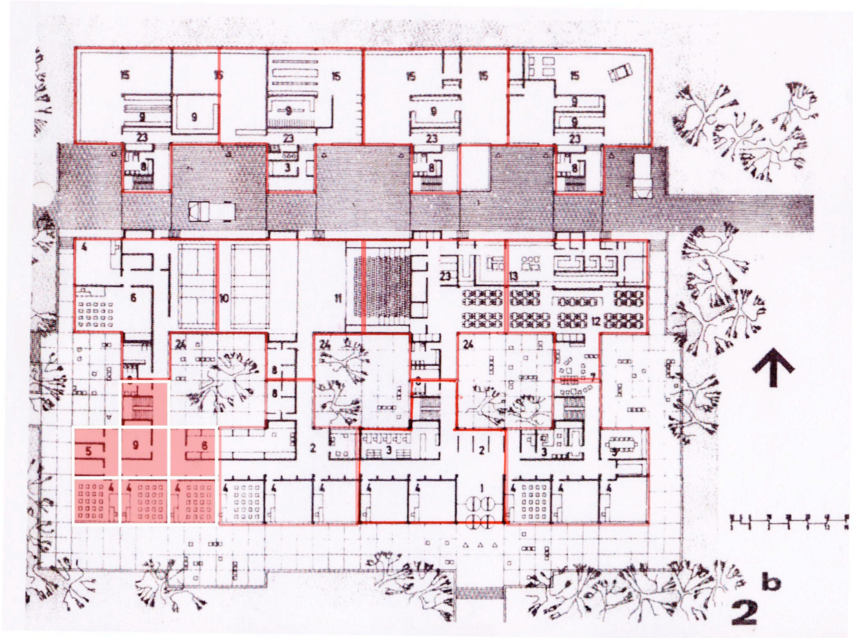
The external envelope (Fig. 3.11) and internal structure of the RTCs have a grammatical interrelationship with the modulated grid, similar to Loughborough and Birmingham precedents. However, both the form and texture of the envelope fall short of higher quality precedents. The choice of a banded envelope emphasises the monolithically horizontal nature of the finger blocks. The silver anodised aluminium contiguous fenestration is overtly legible, appearing to advance forward with vertical mullions, interrupted by spandrels arresting the rhythm of the grid. By comparison, Wishnick Hall's (Fig. 3.15) controlled panel geometry is outlined by a dominant black exposed steel structure, containing planes of different scales, stacked and modulated like soldiers marching harmoniously along the length of the blocks. Wishnick Hall's pronounced vertical rectangular planes, outlined in black steel, are subdivided into four square windows and a cream brick sill panel (which is subdivided again by the rectangular brick and mortar grid) in an almost tatami-like grammar. Loughborough's brick or glass inset walls on the ground floor offer relief from the monolithic nature of the façade, and its projecting exposed structure breaks the continuity of the fenestrated strip along the block length (Fig. 3.15).

Fig. 3.15 Wishnick Hall-left (Mies van der Rohe) & Loughborough-right (Foggio-Arup Associates)

Fig. 3.16 RTC Cork, left (2016) and Loughborough University, right (2011)

The texture and depth of the RTC aggregate panels do not match the fine materiality or control of Loughborough (Fig. 3.16, right), where the texture and tone contrast with the contiguous dark glazed façade. Dark metal glazing frames appear to recede subtly and offer a planar contrast to the warm recessed brick walls. The texture of Wishnick Hall is subtler than that of Loughborough and dependent on the geometry to provide a taut composition of tectonics. The external cladding of the RTC buildings, in contrast (Fig. 3.16, left), is without such close control of texture or grid. The concealed structure, linear strip glazing and poor geometric composition add little in the way of tectonics or proportional grammar. Formally, the RTC composition is poor when compared to its precedents, at Loughborough, Birmingham and IIT.



Figs. 3.16 Waterford T-Unit in plan and perspective
(Building Design Associates 1968)

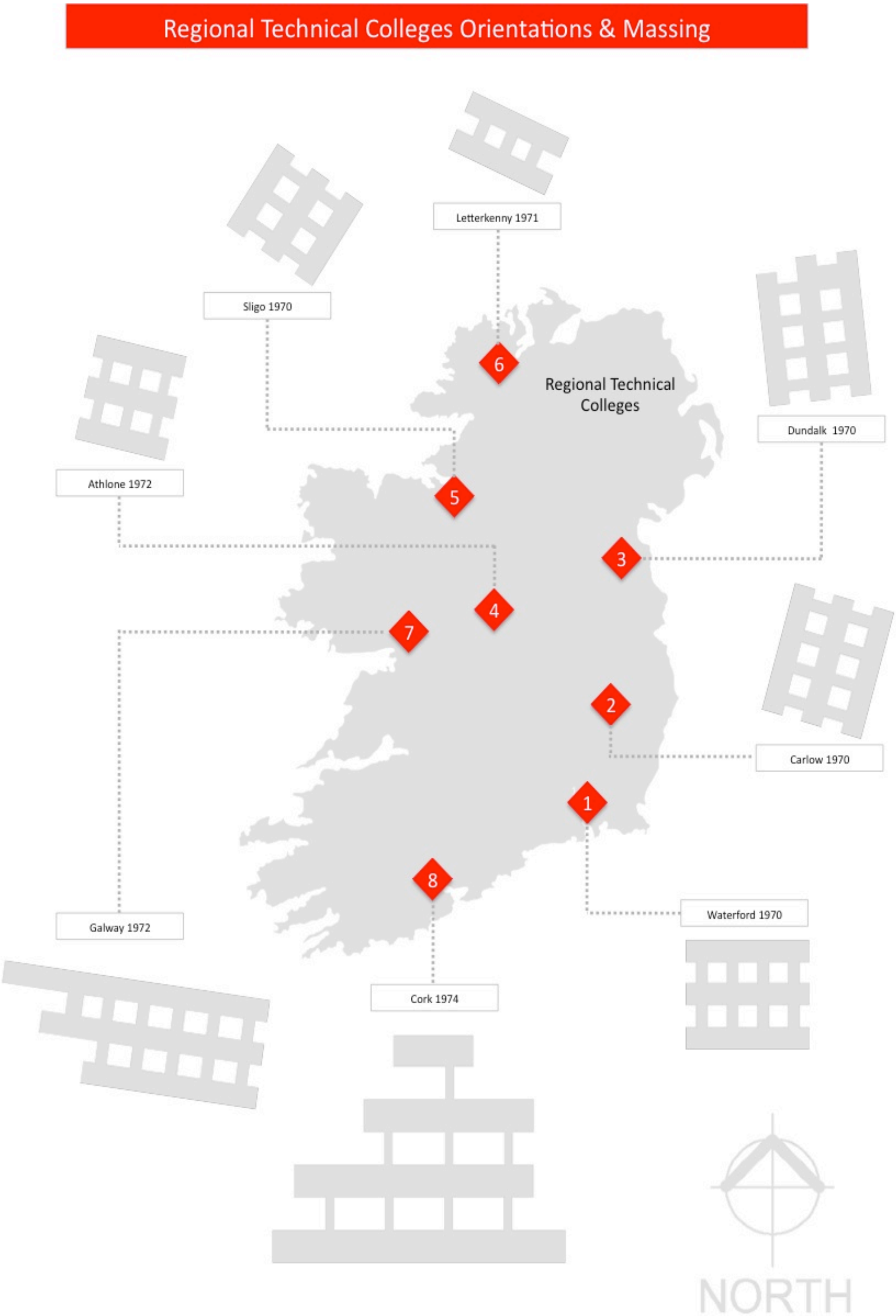


Fig. 3.17 RTC Campus locations, noting the orientation and massing (Ó Riain 2014)

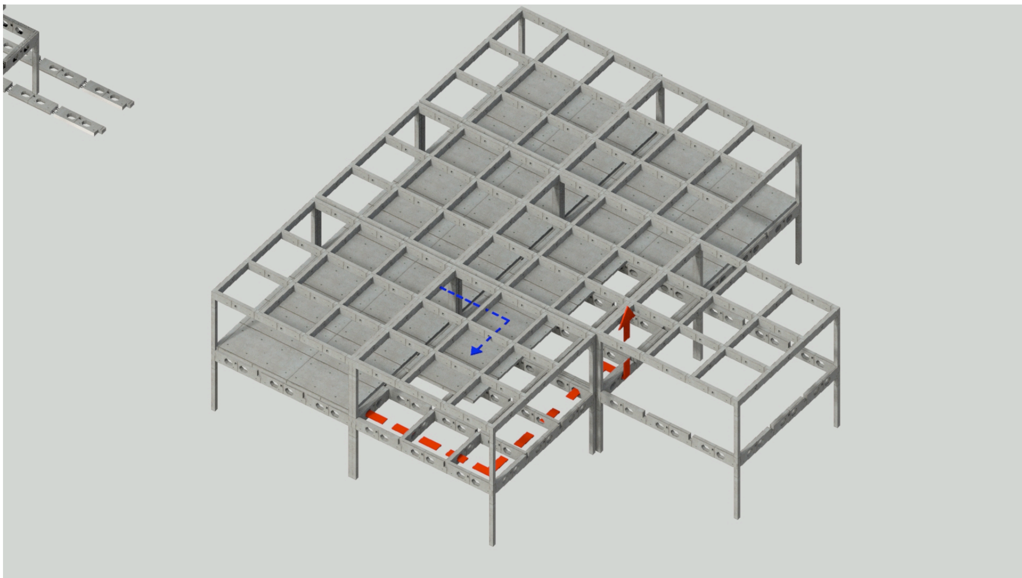


Fig. 3.18 Waterford T-Unit prototype with Integrated Structural Servicing Routes (Ó Riain 2014)

3.6 Formal Domain Typology

This configuration of the final design of the RTC buildings makes it clear that the buildings would be extendable along their length and not their width, thus reducing the impact of construction on an operational college. In all the RTCs (except Cork) the T-Units comprised of outwardly facing classrooms and inwardly facing offices (towards enclosed quads), separated by a corridor, which included vertical riser shafts. In Cork, the T-Unit was made up of 10 two-storey tables, separated by a single bridging table, making the enclosed quads wider than standard. The expanded finger blocks spanned 3 table units (with classrooms on both sides of an enclosed corridor). This is relevant because later developments at multiple sites saw the enclosure of a number of internalised quads. Cork RTC's inward facing classrooms depend on windows for single-sided natural ventilation and natural light, making the enclosure of quads environmentally problematic, leading to the potential for poor air quality and overheating.

3.6.1 Table Structure

The basic table structure (Fig. 3.18) is made up of perimeter reinforced concrete, 600mm deep Vierendeel beams resting on four columns, with intermediate beams (two pairs at 2.4m centres in both directions) resting on the edge beams. Tables were stacked with an identical first floor unit (except for 400 mm deep beams). Tables were clustered side by side, deviating from Dowson's structural column over-check, which had created vertical service and ventilation risers. Floor and roof slabs used four precast concrete panels at each level, overlaid in a tartan pattern, across the structural table's intermediate beams. Side by side, vertical columns were jointed with concrete and grout in situ. Sixty-four millimetres of topping, reinforced with mesh over the plates, complete the structure, with 25mm of Styrofoam insulation under asphalt weathering. Table strength was $31N/mm^2$ and $22m^3$ volume of reinforced concrete.

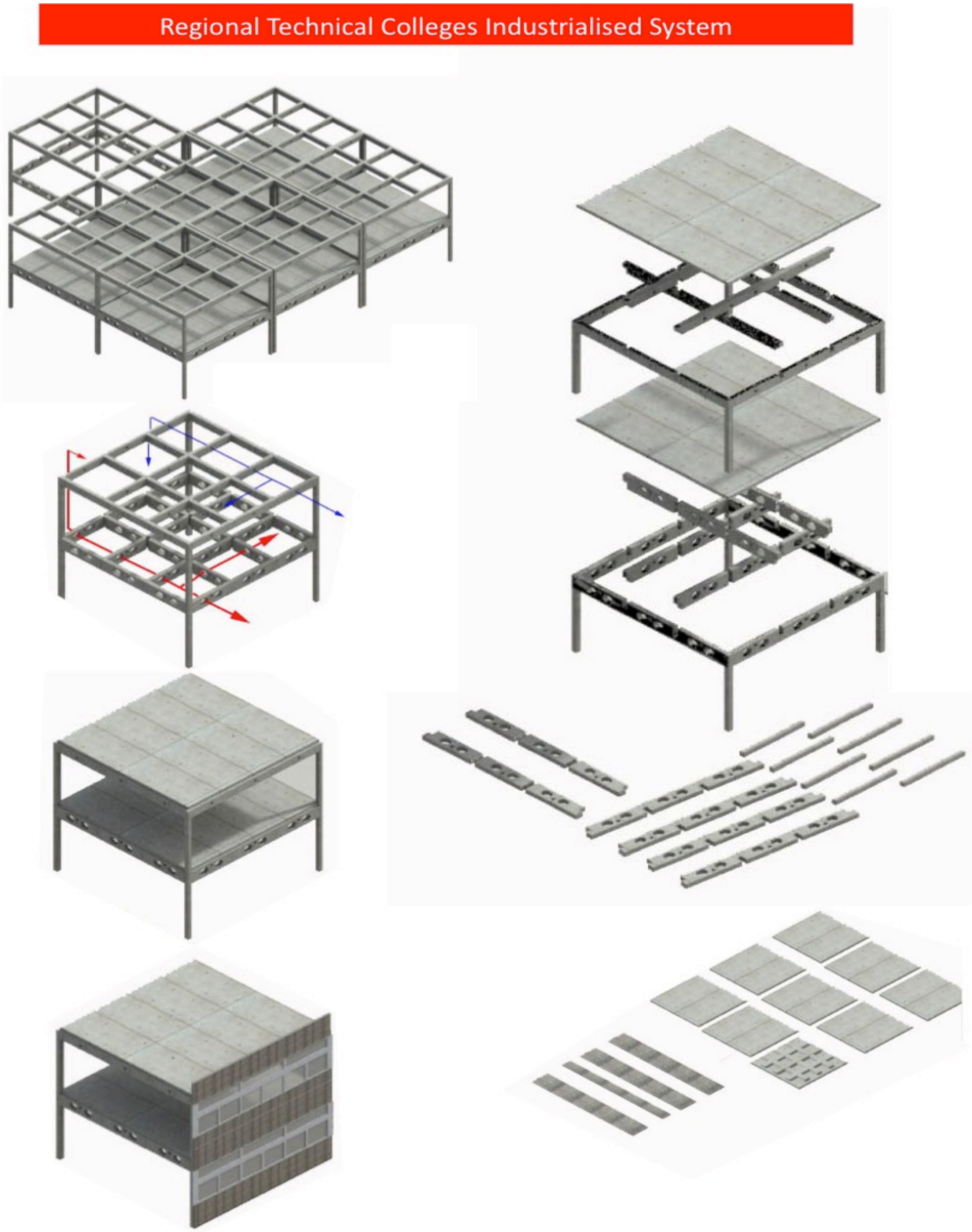
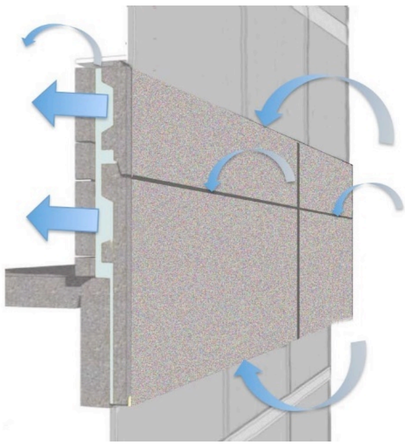


Fig. 3.19 RTC Tartan grid and table Structure, identifying the table structure and servicing (left) and various envelope elements and structural assembly (right) (Ó Riain 2014)

3.6.2 Cladding Panels

Modular cladding panels (Fig. 3.19) (7.2m or 4.8m long, at varying heights of 600mm and 1200mm), with an exposed aggregate finish, concealed the structural frame. Each concrete panel was corrugated with stiffening ribs of 75mm, which were site cast in GRP moulds with steel reinforcement mesh, and were finished with large rough-washed granite aggregate. The modular cladding panels were fixed to the box columns by means of four steel cleats and bolts, using holes cast in the columns. Internal non-structural 100mm block walls ran from column to column on the perimeter, separated from the cladding panels by an un-insulated well-ventilated cavity (Fig. 3.20). Water ingress, particularly at cleat points and narrow cross sections of the aggregate panels, has led to expansive spalling and concrete corrosion, where panels were not sealed post-construction. This, therefore, led to slippage and delamination of panels from the façade at the Cork site (see chapter 6 for more detail). Panel joints and perimeters were originally unsealed, leading to air and water ingress to the cavity and building interior. The continued exposure and hygroscopic profile of the existing panels may lead to future delamination issues to be considered in any retrofit solution. The existing wall cavities are continuous along the blocks, due to the corrugated nature of the panels, which sit in front of them. Therefore, any partial retrofit solutions need to consider the potential for horizontal conduction and convective heat loss along the cavity.



Layer	Description	Dim (mm)
1	Existing internal block	100
2	Well ventilated air gap	86
3	Existing aggregate panel	125

Fig. 3.20 Highly ventilated cavity/ air infiltration/evidence of slippage (left bottom panel) (Ó Riain 2014)

Internal perimeter sill walls were originally capped with a 1.5mm highly conductive aluminium sill plate, offering little defence from cavity-related heat losses. Over the years, many sites have replaced aluminium sills with hardwood sills, although in some cases mould growth was evidenced where cavities were not properly insulated (Ó Fiaich college inspection, Ó Riain 2015).

Fig. 3.21 Existing cladding panels, south-facing, Cork (Ó Riain 2014)

3.6.3 Windows

Single-glazed, milled aluminium, grid aligned frame windows (Fig. 3.21) sat atop the sill aggregate panel and inside the head aggregate panel. Each 2.4m unit comprised of one fixed low-level pane, one opening pane (with 100mm restrictor) and a single fixed fanlight, separated by a spandrel panel, with frame ventilation slot (which were mostly seized or deliberately screw fixed in a closed position post-occupancy). Frames were fixed in position with a grout, which has been locally perishing at many sites, aggravating air penetration.

3.7 Physical findings of the RTC buildings informing retrofit potential

The concrete industrial closed system builds, like the Regional Technical Colleges, with their precast panels, suffer from high conductive and convective heat loss (detailed assessments in Chapter 6). Deteriorating and decaying sealant/baffles to the joints between panels have implications for weather related water and air ingress. Poor levels of air-tightness, surface condensation, a lack of thermal insulation and expensive, uncontrolled heating systems all contribute to significant problems and high heat energy losses for all of the original buildings. Spalling of steel braces and ties holding the aggregate panels onto the building structure impact potential retrofit re-cladding strategies. However, the concrete frame has a longer lifespan potential than precedent steel frame predecessor and has the potential to act as an interior environmental thermal modifier, if exposed as thermal mass.

The original roof design suffered from expansion, resulting in water ingress and, in all cases, is beyond its 40-year lifespan. Thermally drifting Styrofoam in roof insulation and Perspex roof lights allow for high roof-related conductive heat losses. The original windows have a very poor thermal performance and are unlikely to deliver adequate ventilation, with high-level vent slots fixed in closed positions post-occupancy. Well-ventilated, horizontally connected, un-insulated wall cavities ensure high air permeability and convective heat loss. However, the lack of cavity obstruction and low number of panel ties provide an excellent opportunity for cavity insulation. The lack of floor slab insulation creates a difficulty for retrofit solutions, especially with respect to perimeter thermal bridging risk. Continued occupancy, roof-mounted equipment and short inter-semester redevelopment timeframes cause further complications for any retrofit design solutions. Various lightweight, third floor solutions (Letterkenny and Waterford) establish the potential for vertical extensions. Orientations are not common, nor potentially optimal, with a high glazing factor, but the compact nature of the blocks may result in more optimal area-to-volume factors for retrofit.

3.8 Formal Domain: The influence of the client on the artefact outcome

By the mid-1960s, Ireland was on an economic upswing and the new Minister for Education, Donogh O'Malley, set about an ambitious building program, establishing the Regional Technical Colleges in 1966. The program set out to address a massive social inequity, whereby a child was

68 times more likely to go to college if they had upper class parents (than if their parents were of the manual classes) (OECD 1962)[261]. There were 10 times more professional graduates coming out of university than technicians coming out of further education (OECD 1964)[262]. The government, industry and the World Bank all recognised that this was becoming a serious threat to the potential for continued national economic growth; a change had to be made.

Embracing the systemised construction ethos, O'Malley structured education like an assembly line, delivering the children of the working classes to second and then third level education, on a scale never seen before in Ireland (Hyland and Milne 1992)[263]. He grasped power away from local church-dominated vocational groups, under whose oversight school design had been allowed to develop in haphazard and often obscure ways (Hyland and Milne 1992). Making an executive parliamentary decision, he announced his intention to set up the RTCs in 1966 (O'Malley 1966)[264], quickly establishing a steering committee to inform a design brief. This move emasculated an existing Commission on Higher Education, whose recommendations remained unpublished until 1967 (Breathnach 1968)[265].

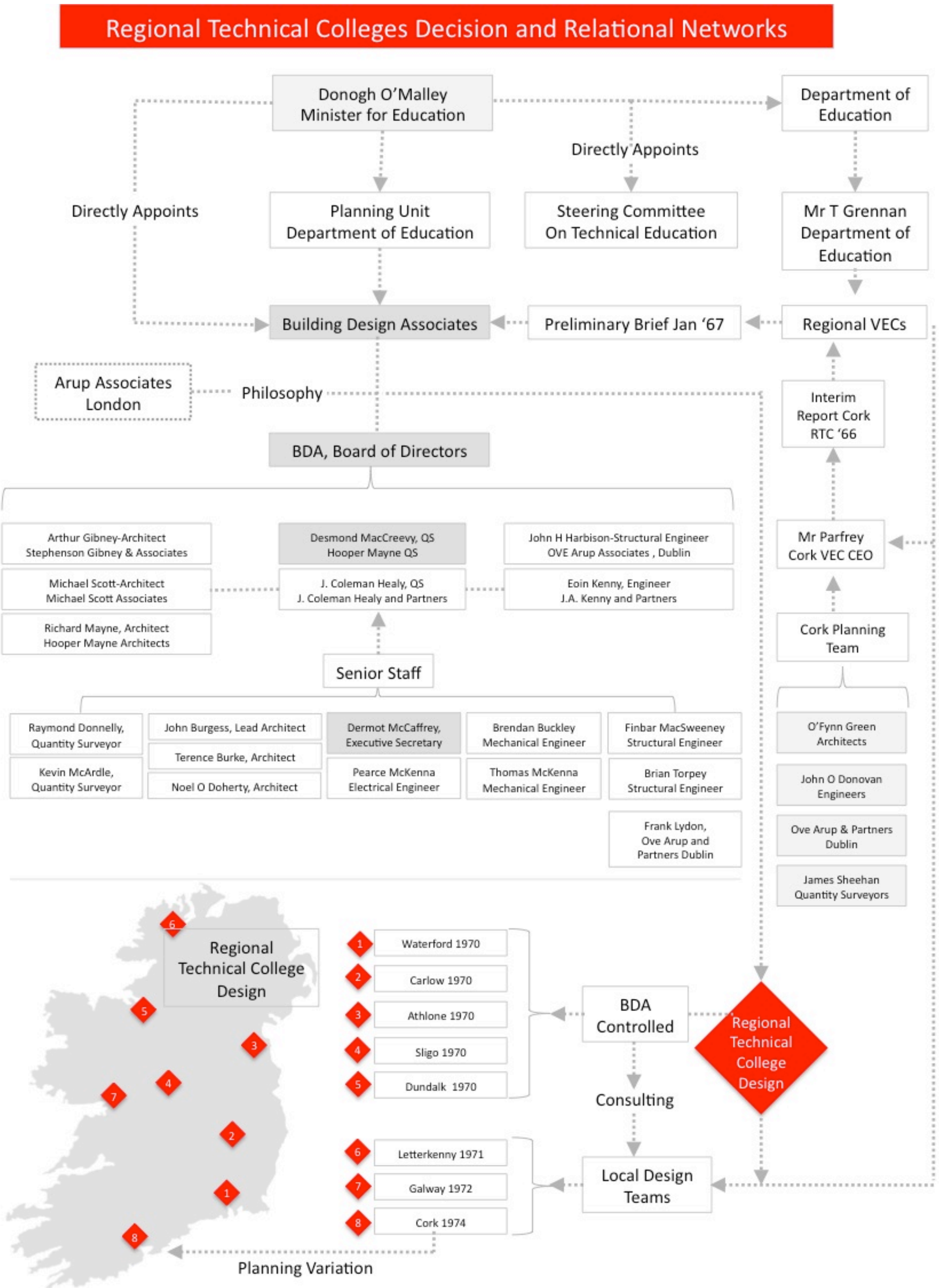
3.8.1 The Minister for Education, a political maverick

Ignoring the existing regional appointments, O'Malley handpicked the team he wanted for the largest multi-site construction project in the history of the state, under the guidance of Desmond McGreevy, a close friend of O'Malley's and political party chief fundraiser. The new design-team formed as a consortium called Building Design Associates (BDA) (Healy 1988)[266], included Michael Scott, Arthur Gibney, J. Coleman Healy, Eoin Kenny and Arthur Mayne, with Arup's leading engineer, Jock Harbinson (BDA 1970)[267]. The Minister required a 3-year design and construction period, commencing in late 1966 and completing the first phase of five buildings in September 1969, with a 20% cost and time saving over traditional methods. The design team was refused a research trip to IIT Chicago in an uncouth manner from the Minister, who reportedly responded to their request with: "I'm not going to pay you fuckers for investigating colleges and universities and whorin' round the world" (Healy 1988). Scott and Gibney had clearly looked towards IIT for precedent, but political forces pointed the design team towards a more local precedent. In response to criticisms over the BDA appointment, O'Malley made separate appointments for project design teams at Letterkenny, Galway and Cork sites, effectively separating the design ethos from the construction stage. BDA members confirmed they spent very little time on site (McSweeney 2014). Political intervention created a process discontinuity, reflected in Graph 3.6.

3.9 RTC Cost

Prior to the construction of the RTCs, Irish education "buildings were to a large extent uneconomical, with high ceilings, single-loaded corridors, expensive materials, and very little standardisation of teaching accommodations" (World Bank Operations Evaluation Department 1980)[268]. The initial RTC design was proposed by BDA in March 1967. It included standardised accommodations and double-loaded corridors. The design had only 5 months for development and was delivered only a month after the research trip to Birmingham and Loughborough. The project was budgeted and presented to the Irish Parliament at a cost of IR£8.4m for 9 college campuses. This could be broken down to IR£6.87 psf (IR£74m^2), which, in April 1967, was "low by both Irish and British standards for this nature of project" (Department of Education 1968)[269]. Parliament demanded further savings of 16.4% (Oireachtas 1968)[270]. This resulted in further value engineering decisions, resulting in the project becoming very cost centred (Burgess 2014). The brick internal walls of (Birmingham and Loughborough) precedents could not be afforded and were replaced with fair faced concrete block, internal parquet floors were replaced with linoleum coverings, equipping budgets were all cut back, and the independent column structures would now be cast together, abandoning the architectural ethos of 'unity and flexibility' (Department of Education 1968)[271].

Part project financier, the World Bank became critical of the RTC design. "The serious fault with all building designs in the [RTC] project lies in the high energy consumption aspect. Basically, there has been inadequate cost provision to meet environmental (heating and ventilating) engineering needs" (World Bank Operations Evaluation Department 1980).



Graph. 3.1 Relationship mapping for Regional Technical Colleges, highlighting the complex interaction of factors and influences. The BDA controlled projects are separated from projects at Letterkenny, Galway and Cork where client/political input resulted in separate project design teams. (Ó Riain 2015)

The declassified World Bank report included post-occupancy surveys of the RTCs, which found that the roof was susceptible to thermal expansion and failure. A user survey in 1980 found noise transfer was an issue between classrooms, due to poor detailing at glazing walls and partition-to-slab junctures, with 64% of people finding the acoustic insulation to be poor.

User dissatisfaction was expressed with the following elements:

- Boundary walls (64% poor)
- Inadequate parking (18% poor)
- Windows (50% poor)
- Doors/ suspended ceilings (16% poor)
- Heating installation (42% poor)
- Landscaping (45% poor)

  (World Bank 1980)

The World Bank report conceded that a number of key façade features and active systems were contributing to the poor energy performance:
"Among the features which presently cause functional discomfort and heat losses are:

(a) The extent of use of single-pane glass;
(b) Inadequate roof insulation; and
(c) High consumption and maintenance heating systems."
(World Bank 1980)

The 1967 budget for Cork RTC of £1.45m more than doubled, with the eventual cost coming in at £3.2m (World Bank 1980).

3.10 Conclusions

The UK Department of Education and London City Council were well used to the use of modular and precast systems constructions, which became popular in the wake of the Second World War. By the time Dowson and Foggio went to design and build Birmingham and Loughborough Universities in 1965-66, the rationalisation of the system build had been well developed with centralised procurement and the minimisation of componentry. Changes in political priorities in the early 1950s moved the industrialised system away from steel frame to concrete frame, with a loss of composition and tectonics in architectural language.

The architectural style of Brutalism developed from a number of educational precedents, where an exposed frame, quality materiality and finish were important to the affordable industrial construction. However, as the systems developed, columns were inset, resulting in a concealment of the grid by aggregate concrete panels, resulting in a more 'plastic' finish, but ultimately resulting in less 'delight' than that of Hunstanton or IIT. Both the International and Brutalist precedents, with their plastic envelopes lacking relief and shading, evidence a lack of architectural priority for environmental functionality, with Hunstanton being a clear example of this. The concealment of the structure and an emphasis on rationalisation created "visual squalor; [where a] technical over emphasis can lead to anti-social building, an end in itself devoid of humanity, where the medium is the only message" (Delaney 1970)[272].

However, from a retrofit point of view, the relatively poor external aesthetic of the Regional Technical Colleges makes them ideal for external re-cladding, and the lack of exposed external structure minimises thermal bridging risk in low-energy retrofit. Arup Associates' *Total Architecture* buildings of Loughborough and Birmingham Universities evidence an intelligent and innovative cross-disciplinary approach to design, delivering quite an advanced environmental solution, as yet unrealised in the Regional Technical Colleges. The potential for thermal mass to play an important role in moderating the internal thermal environment informed the pilot-project retrofit.

In retrospect, it is sometimes difficult to perceive why buildings are the way they are. The International and Brutalist styles of architecture were of the era and promised a more egalitarian world. But, as is often the case, they proved easily corrupted by politics and myopic decision-making. The lack of both architectural continuity and adequate time to properly detail the RTC design scheme meant that the largest multi-site development in the history of the state delivered an ugly (Mills 1974)[273], uncomfortable building with a poor environmental performance.

The technology of concrete, the development of systemised prefabrication, construction speed, architectural brutalism, immediate precedents, cost and political decision-making became the central forces that would shape the design of the Regional Technical Colleges. Because of time constraints and a lack of research, the building designs were not focused on educational theory or internal environmental functionality, and certainly not on operational costs. Architectural priorities would change following the first oil crisis of 1973/4. The next chapter deals with the emergence of the Environmental Movement and its impact on built environment legislation, the oil crisis of 1973/74, the political response to the crisis and the emergence of Zero Energy Building Performance, which contextualises energy conservation design in building design today. The next chapter will seek to explore how the political and socio-economic fields have the ability to promote or undermine the case for low-energy buildings.

CHAPTER 4

EMERGENT EXEMPLARS IN LOW ENERGY BUILDING DESIGN AND THE LEGISLATIVE CONTEXT TO ENERGY IN BUILDINGS

Chapter 4: Emergent exemplars in low-energy building design and the legislative context to energy in buildings.

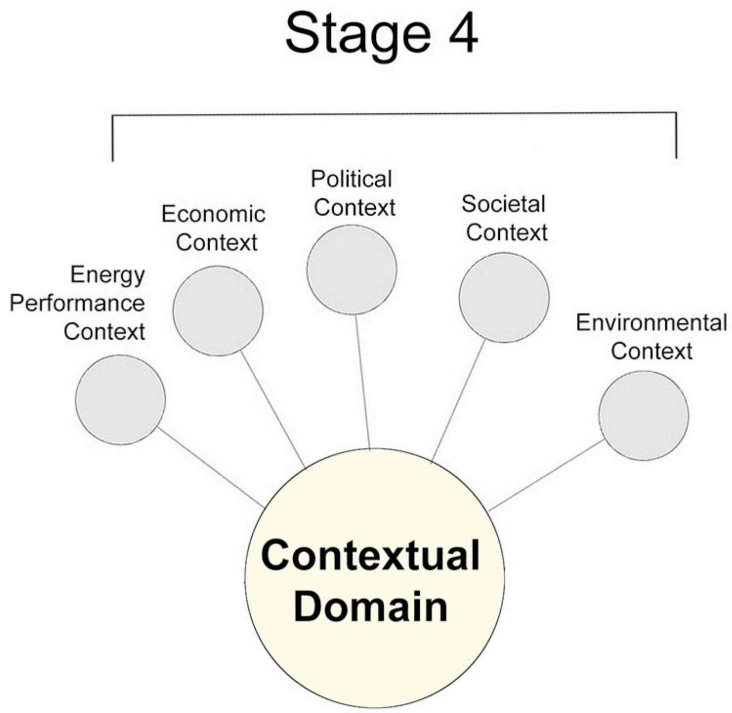
4.1 Methodological Statement

Following Foqué's *Product Context Process* analysis (PCP), the goal of this domain stage is to examine the *Contextual Domain* (Graph 4.1), mapping and understanding the relational network linking the different contextual components of society, politics, economics, architectural theory, style, technology and precedent in advance of the actual design period (Foqué 2010)[274]. The product engenders the 'building genome', composing the data that influences the design process and its functional form. Therefore, the establishment of an artefact's context can help explain the influence on the design process, eliciting facts about the building's design and construction. The *Contextual Domain* includes the various factors that influence the formal building and architectural praxis. The *Normative Domain* includes the socio-political framework around which buildings are created, the regulations, incentives and laws. In examining the published literature, Stage 4 summarises the process stages from the *Contextual Domain*, mapping the relationship between rising public awareness of environmental issues and their societal/political response. The domain attempts to place the original RTC design at a pivotal point in time where the oil crisis (1973/74) influences the geo-political and socio-economic spheres. All of this stage is based on secondary sources.

4.2 Introduction

"GHGs (Green House Gas) are un-costed externalities, there are no compelling reasons, beyond profit maximisation, for companies to choose a lower GHG-emission strategy over a higher one when they are planning new processes or products."

(Watson et al. 1996)[275]



Graph 4.1 Stage 4 *Contextual Domain*

Watson identified that unless the external costs of fossil fuel consumption were internalised into the cost of the fuel, then companies were unlikely to choose a more expensive option, which mitigated externalities like GHG emissions.

McKinsey (2009) asserted that low-energy building retrofit is one of the most cost-effective measures for GHG abatement, yet despite the development of the first Zero Energy Building (ZEB) in 1975 (Esbensen and Korsgaard 1977)[276], Altwies and Nemet (2012, p 819)[277] found that market adoption of low-energy buildings has suffered a variety of market barriers, "despite the implementation of an array of policy instruments aimed at promoting efficiency" (Altwies and Nemet 2013); low-energy buildings have not gained widespread market adoption. Fraunhofer (2009) found that "lower diffusion rates of the best available technologies" suffer from a number of heterogeneous barriers, including policy and affordability (Fraunhofer 2009)[278]. The existing low level of legislative policy intensity and the low level of building retrofit energy compliance are highlighted as key barriers to a more widespread diffusion of low-energy strategies (Antonelli and Colley 2012) [279]. *Passive Plus* magazine illustrated low levels of new buildings' code compliance with Regulations in 2011 (Antonelli and Colley 2012)[280]. A similar culture of industry non-compliance with energy in buildings regulations can be observed in the UK, largely due to the lack of enforcement.

Blomsterberg and Engvall (2011)[281] reported that many of the market barriers to the adoption of low-energy building solutions are non-technological. Decisions on building development are much like consumer product decisions; Hausman (1979)[282] reported that consumers often undervalue operational energy cost when making decisions between energy efficient options. Indeed, Austin (2012)[283] argues that the availability of technological solutions may not be the critical problem in GHG reduction though retrofit, but other economic and legislative issues may be influencing "market barriers and adoption behaviours" (Austin 2012)[284].

The objective of Stage 4, the *Contextual Domain*, was to review the heterogeneous influences and macroeconomic changes since the 1973/74 Oil Crisis, and their bearing on the adoption of low-energy building design. This was done to establish the variable factors influencing both the development of technological solutions and legislative tools, promoting greater energy efficiency in buildings and how this is impacting the potential for NZEB retrofit adoption in an Irish context today.

The *Contextual Domain* stage links chronological exogenous events to public energy policies and the subsequent development of low-energy legislation in the built environment field, with an examination of international conditions and motivations for legislative change. The stage also notes the impact of volatile fossil fuel energy prices on market demand for energy conservation measures, and renewable energy. The chapter will illustrate how oil prices and oil security drove international policies, up to 1986. Subsequent events would go on to inform the current low-energy regulatory framework. The initial experiments with low-energy building design were mapped. Next, the research examined the major paradigm shift in environmental geopolitics from 1986 to 2010, which drove national policies and incentivised energy efficiency in buildings. The contextual analysis discovered that the environmental debate played a relatively minor role in driving energy policy up to 1986, and illustrates the need for sensitivity and scenario analysis for economic efficiency evaluations to account for uncertain future energy cost conditions (Slaughter 2013)[285].

The *Contextual Domain* stage sets a scene for a discussion on cost-optimisation methodologies for low-energy retrofit in the next chapter.

Irish Building regulations Progression of Energy conservation in Buildings (Dwellings)Average Elemental U-Value in W/m^{2}K								
W/m^{2}K	**1976**		**1991**	**1997**	**2002**	**2005**	**2007**	**2011**
Roofs (flat)	0.4		0.4	0.35	0.25	0.25	0.22	0.2
Walls	0.6		0.6	0.55	0.37	0.25	0.27	0.21
Ground Floors	0.6		0.6	0.45	0.37	0.25	0.25	0.21
Av Elemental Improvement			0%	15%	10%	22%	1%	19%

UK Building regulations Progression of Energy conservation in Buildings (Dwellings)Average Elemental U-Value in W/m^{2}K								
W/m^{2}K	**1976**	**1985**	**1990**	**1994 (SAP<60)**	**1994 (SAP>60)**	**2000**	**2005**	**2010**
Roofs	0.6	0.35	0.25	0.2	0.16	0.25	0.16	0.16
Walls	1	0.6	0.45	0.45	0.35	0.45	0.35	0.35
Ground Floors	1	0.6	0.45	0.35	0.25	0.45	0.25	0.25
Av Elemental Improvement		40%	25%	13%	24%	-32%	32%	0%

Table 4.1 UK and Irish Building Regulations, U-Values evolution (1974-2011) – Ó Riain 2016

*SAP allowed a cost-optimal investment level

4.3 An Exogenous Event - *The OAPEC Embargo*

In October 1973, as people were filling their home heating tanks with oil at $2.59 per crude barrel, an Egyptian and Syrian offensive against Israel resulted in the Yom Kippur War. The subsequent rout of the Egyptian 3rd army at Suez by Israeli forces, supported by arms from the US, resulted in an OAPEC oil embargo against the West, in retaliation (Merrill 2007).[286] This caused a scenario, echoed by Schumacher and the Club of Rome, where a depletion of resources could lead to economic and societal collapse. Within the year, the cost of a barrel had quadrupled to $11.65 on 1st of January 1974 (Scott 1994)[287]. OAPEC fixed prices at $11.65, 400% over the early 1973 price, and reduced supply, causing reserves in non-oil producing countries to be depleted quickly, effectively reducing Gross National Product (GNP) and increasing unemployment (Jackson 1978)[288]. This brought industrialised countries to realise the extent of their economic exposure to foreign imported oil (Scott 1994)[289]. Merrill argued "the oil crisis was understood to be both a difficult international issue and an environmental problem" (Merrill 2007)[290]. Casey (1973) reported to the US senate that "our natural resources, whether fossil fuels or ores, however immense, are finite. We must learn to use them efficiently. We must learn to conserve" (Casey 1973)[291].

The oil embargo ended in March 1974 but resulted in a changed political dynamic. US President Nixon (Foreign Relations of the United States 1974)[292] saw the required short term response of energy conservation as a "burden" upon the public, yet under the tenure of the subsequent US President, Ford (1974-1977), energy conservation measures would become a central part of government policy. The foundation of US policy, under Ford, was "more fuel efficient cars, better insulated houses, and less wasteful appliances" (Merrill 2007).

Driving an international reaction to the OAPEC embargo, the 24 OECD member countries, representing 85% of world oil consumption (Nixon 1974)[293], came together in Washington at an Energy Conference led by the US and Henry Kissinger, on February 11 to 13, 1974. "The Foreign Ministers of Belgium, Canada, Denmark, France, the Federal Republic of Germany, Ireland, Italy, Japan, Luxembourg, the Netherlands, Norway, and the United Kingdom attended" (Foreign Relations of the United States 2011).

The topics to be discussed were:

- Energy conservation,
- Alternative energy sources,
- Research and development,
- Emergency sharing,
- International financial co-operation,
- Less developed countries,
- Consumer-producer relations.

This provided the basis for discussions as US President Richard Nixon adopted a policy for energy self-sufficiency, entitled *Project Independence 1980*. This policy became central to US and UK domestic and foreign energy policy for nearly two decades.

The US had already set up a Federal Energy Administration in December 1973, in reaction to the oil crisis (Anders 1980)[294]. Tasked with implementing the goals of *Project Independence 1980*, which was based on energy self-sufficiency from imported energy, the administration looked at methods for increasing US non-renewable fossil fuel extraction and researched applications of renewable energy such as solar water heating and geothermal heating. It also established a number of energy conservation measures; Utilities Conservation Action Now, Voluntary Energy Conservation, (Anders 1980)[295] and Minimum Performance Standards for all public housing developments (HUD-MPS 74) were instigated through section 526 of the Housing and Community development act of 1974 (De Simone 1979)[296].

At the February conference (1974), Kissinger urged that a new International Energy Agency (IEA) be established, to focus on energy "conservation, alternative energy sources, research and development, emergency sharing, international financial co-operation, the less developed countries, and consumer-producer relations" (Foreign Relations of the United States 2011)[297]. Initial discussions amongst the

OECD member countries at the Energy Conference (Feb 1974) led to the eventual formation of the International Energy Agency in November 1974 in Brussels (Scott 1994)[298].

The first aim of the IEA was:

> *"Co-operation among IEA participating countries to reduce excessive dependence on oil through energy conservation, development of alternative energy sources and energy research and development."*
>
> (Scott 1994)

Both US and OECD actions demonstrate that the external factor of the oil crisis was the dominant driver of energy conservation legislative action and renewable technology research in the early 1970s for up to 85% of the oil consuming nations, rather than the environmental lobby.

Following Nixon's replacement by Ford in 1974, the Federal Energy Administration introduced the *Energy Policy and Conservation Act* in 1975, "to establish energy efficiency standards for household appliances, to make grants to state conservation programs, and to monitor the energy efficiency of the fifty largest energy-consuming industries" (Anders 1980)[299]. This resulted in greater efficiencies in consumer products such as air conditioners and furnaces for buildings, but lacked coherent federal policy for the built environment, apart from the Weatherization Assistance Program in 1976 for low-income families to improve door and window seals to promote energy conservation. The Energy Conservation Standards for New Buildings Act was introduced in 1976 (De Simone 1979)[300]. When Democratic President Jimmy Carter took office in 1977, he referred to the oil crisis as "the greatest challenge our country (US) will face during our lifetimes" (Ross 2013)[301]. He set out specific targets to be achieved by 1985: "insulate 90 percent of American homes, all new buildings and use solar energy in more than two and one-half million houses" (Power 1977)[302]. This was the first instance of federal efforts in the US towards energy conservation in buildings and the use of renewable energy, thus giving great confidence to the market developing energy efficient homes using renewable technologies. In 1979 the US Department of Energy proposed Building Energy Performance Standards (BEPS) (US DOE 1979) that set maximum energy performance levels for both (Levine 1979)[303].

Political sensitivity to energy remained focused by similar sharp shocks in energy prices over time. World dependence on oil had increased and attracted political volatility to many production countries. Adjusting for (US) inflation, the relative cost of a barrel of oil maintained an upward curve from $20 in 1973, peaking near $120 in early 1974, and falling back to $30 per barrel in 1985 (a similar rate to January 2016). As the prices rose due to the OPEC embargo, governments responded to the energy security issue by making energy efficiency part of policy, leading to investment in building energy conservation measures.

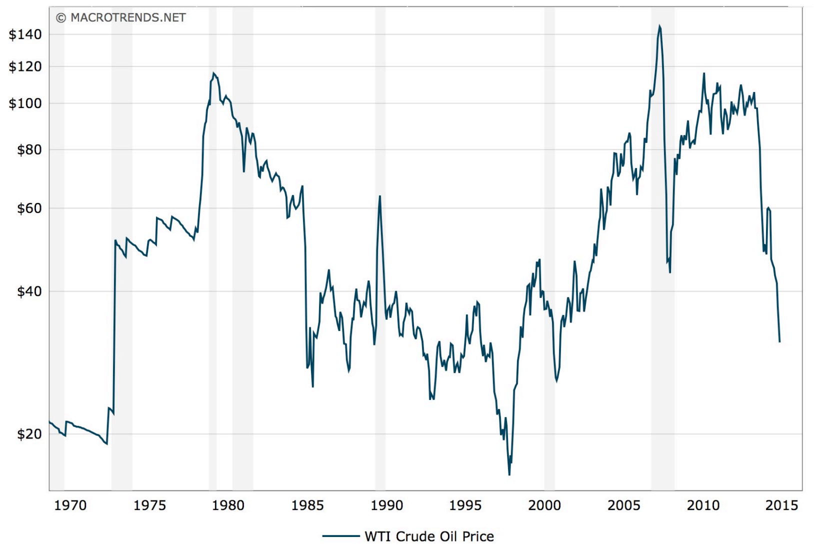


Table 4.2 Inflation Adjusted Oil Prices 1970 - 2015 (macrotrends.net)

However, the sheer volatility of imported energy prices has a serious impact on industry, economy and politics as a result. The cost of oil became a key driver, exerting a decisive influence on the political agenda (Steinmüller 2008)[304] and has had a direct impact on the cost of operational energy for buildings including heating, hot water and electricity. As the price goes up, consumers become more aware of

inefficiency in energy conservation of our buildings, and as the price goes down, energy conservation measures become economically less attractive (Steinmüller 2008)[305]. Equally, without regulated minimum energy performance standards for new buildings, developers are much less likely to realise a return on investment from additional energy conservation measures, in a competitive market-driven economy. In the absence of national regulations on existing building energy performance, 'Return on Investment' (ROI) methodologies for energy retrofit is, thus, more open to impact from the volatility of oil prices, than in new builds. In turn, uncertainty of financial viability represents a market investment disincentive for low-energy retrofit strategy. "As an example, builders have little incentive to add insulation beyond technical norms to new homes when it is the home-owner, not the builder, who will enjoy lower energy bills during the next decades" (McKinsey & Company 2009)[306]
(This issue is analysed in further detail in Chapter 6).

4.4 Low-Energy Pilot-projects of the 1970s

After the first oil crisis of 1973/74 and the formation of the IEA, a number of constituent countries invested in applied low-energy building research. The following buildings have become important precedents in the development of contemporary low-energy design strategies, informing both architectural practice and public policy.

Prior to the oil crisis, there were a significant number of solar house designs in the USA and some research on solar water heat collectors. Solar house designs focused on building orientation, solar heat gain and shading. The German *Passive Haus* standard would not be developed until 1988, but would go onto inform EU legislation for the built environment and the development of the Energy Performance in Buildings Directive (2010). The *Passive Haus* standard would be informed both by pre oil crisis (1973) solar house designs and the post oil crisis low energy houses. The following exemplars focus on a number of these buildings, which would inform best practice in low and zero energy buildings.

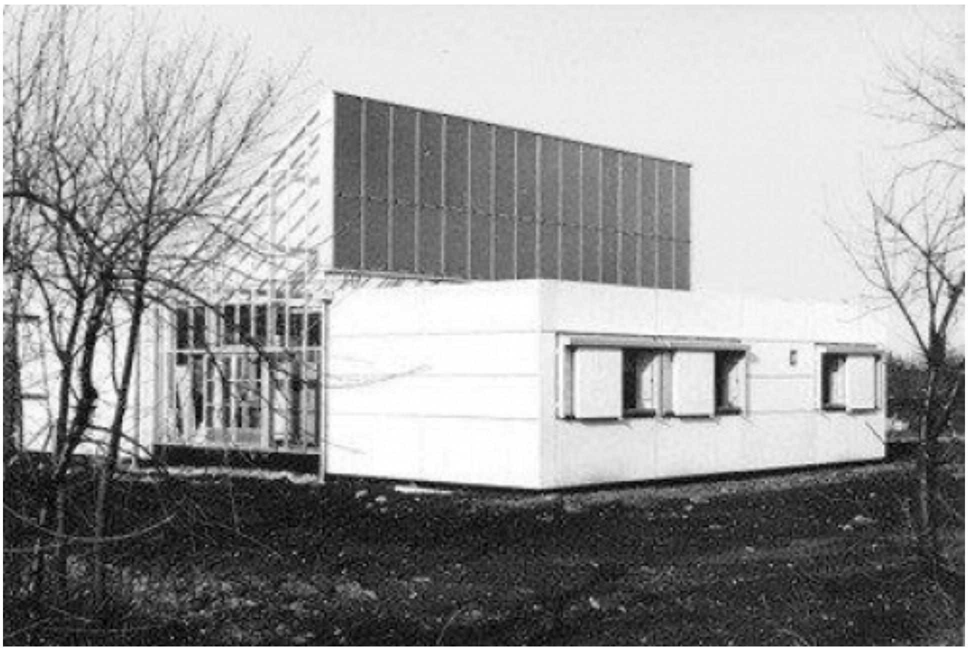


Fig. 4.1 Zero Energy House, Lyngby, Copenhagen, Denmark built 1974 - 1975.(Esbensen and Korsgaard 1977)

4.4.1 Denmark (1974-75)

The first Zero Energy House, Null Energihuset, was developed in Copenhagen immediately after the first oil crisis (Esbensen and Korsgaard 1977)[307]. Denmark supported the first Zero-Energy House designed and built by Vagn Korsgaard and Torben Esbensen in Copenhagen in 1974/75.[308] Two super-insulated airtight buildings with insulated roof (0.14 W/m^2K), walls (0.10 W/m^2K) and shaded double glazed windows (3.1 W/m^2K) were built, separated by a glazed atrium. The buildings minimised energy demand by reducing space heating and cooling with space heat demand at 11.5% of a standard house equivalent. Active systems augmented energy performance with heat recovery ventilation and a wastewater heat recovery pump (50% efficiency), thermal solar heat collectors and an underground insulated seasonal storage tank (Esbensen and Korsgaard 1977). The basic principles of what would become Passive House Design in 1988 (Klingenberg 2014)[309] were established with this experiment: passive energy conservation through a super-insulated and airtight envelope then augmented with active renewable systems.

The potential of energy conservation through insulation and air-tightness, solar shading, active systems such as heat recovery, solar panels, seasonal buffer tanks and orientation were all tested, and the principle of a mixed modal approach to seasonal variation in energy potentialities had been established. In varying from passive solar house predecessors, this new mixed mode approach would become known as Active Solar building. The 1977 paper on the research building clearly identified performance of the building and its constituent elements, but not the concurrent costs of them. The paper highlighted that 88.5% space heat demand savings could be made through envelope thermal efficiency, internal heat gains and passive solar heat gains. The active systems investment focused on the balance of space heat demand (2300 kWh/yr) and hot water demand (2260 kWh/yr). The seasonal storage tank also suffered losses of 38% solar-generated heat energy through conductive loss per year.

Dr Wolfgang Feist, who would go on to develop the Passive House Standard, was heavily influenced by this project; "The Danish zero-energy experiment was one of the very first of its kind and was certainly one of the most systematic. The published project findings were incorporated into Passive House research right from the start" (Antonelli 2013.)[310]. The project also influenced the design of the Saskatchewan Conservation House, 1977(Besant, Dumont and Schoenau 1979)[311].

Fig. 4.2 Phillips Experimental House, Aachen, Germany (1974) (Steinmüller 1979)[312]

4.4.2 Germany (1974-75)

In Germany, Phillips and Dr Horst Horster built the Experimental House in Aachen in 1974, to test the potential of active technologies, such as solar water evacuated tube collectors, a seasonal storage tank (11,000 gallon), heat pumps and a heat exchanger (Lee 1977)[313]. The super-insulated 116m^2 house had energy efficient windows and shutters, combined with air-to-air ventilation heat recovery running at 90% efficiency and two soil heat exchangers. The project reduced space heat demand to 30 kWh/m^{2}a (a factor of 15 times lower than a standard contemporary house). "Accordingly, with respect to "normal" houses, it was possible to reduce the heating requirement by a factor of 10 to 20 in all climates, simply by improving the passive characteristics of such a house. In fact, it appeared that in most climates these efficiency measures are much more effective than measures on the supply side" (Bruno 1978)[314]. Thus, the paradoxical result - for a company, which set out to exploit the supply side potential - was that demand-side measures should receive top priorities (Steinmüller 2008)[315]. The Phillips House established the principle of passive demand-side reduction first, before active solutions, through insulation, air-tightness, orientation and passive solar heat gain.

4.4.3 USA (1939 - 1979)

Fig. 4.3 Hottel's MIT Solar One, 1939. (Shreve 2013)

There is a significant history of solar design for energy efficiency in the USA from the late 1930s. Some examples will be outlined here, but in most cases these are solar solutions, without a high level of insulation. The chapter focuses on the impact of the aforementioned oil crisis on energy conservation in buildings post-1973 and limits selection, to the extent possible, to examples with supporting published and reviewed literature.

With solar design like Keck's pioneering Duncan & Kellet Houses (1941) to Frank Lloyd Wright's *Solar Hemicycle* (1948), Maria Telkes' Dover Sun House and solar heating system (1947), America's interest in low-energy building through solar energy had a rich history (Koehler 2014)[316]. MIT's Solar One building (1939) may have been one of the first active solar buildings, which used an "unusual amount of insulation" (Shreve 2013)[317]. Solar One, with its roof-mounted solar energy collectors and insulated brine-filled, seasonal thermal storage (17,000 gallons) (Lee 1977), informed the development of the Saskatchewan Conservation House in 1977 (Besant, Dumont and Schoenau 1979)[318]. These early precedents of passive and active solar buildings may have influenced, as Denzer put it, the "solar counter culture" of the 1960s (Denzer 2008)[319]. However, "as oil started to become cheaper, the up-front costs necessitated by increased glazing contributed to developers' refutation of the solar house premise" (Barber 2014)[320]. By the 1970s limited instances of hybrid housing started to emerge and become known as *active solar* (with active solar water appliances) (Schick et al. 1979, p107). The OAPEC embargo of 1973 and the aims of Nixon's *Independence Project* shifted the priority towards energy conservation in buildings in 1974-75. The following projects demonstrate a movement away from passive solar houses towards active solar and super-insulated houses.

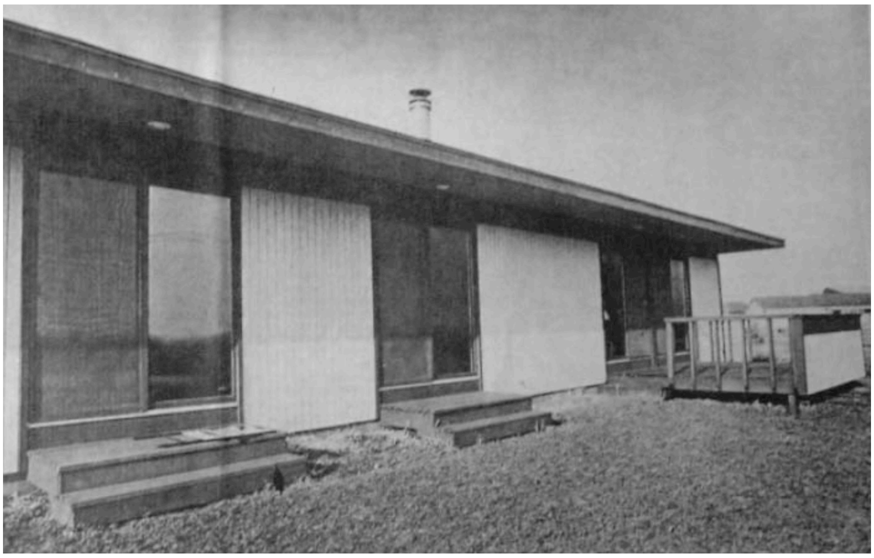


Fig. 4.4 Richard Bentley's Double Wall House, patented 1976 USA (Bentley 1976).

4.4.4 Arkansas trusses (1974)

An early exemplar of this movement towards demand-side energy conservation would be the Arkansas Project (1974) by Tschumi, Blades and Holzclaw (US Department of Housing and Urban Development - HUD). The design led to the construction of dozens of insulated (R-19) houses on raised heel trusses, that became known as '*Arkansas trusses*' (Lstiburek 2009)[321]. The project was focused on creating more airtight and insulated envelopes, to allow them to sell more heat pumps. According to Lstiburek this project pioneered energy conservation in US housing.

4.4.5 Double Wall House (1974-76)

By 1976, two separate private developments in low-energy housing had occurred. Richard Bentley patented the Double Wall house (1974)[322] and Wayne Schick (University of Illinois at Urbana-Champaign) developed the Tschumi-Blades concept to create the Lo-Cal /Low-Calorie House in 1976 (Schick 1979)[323] (Fig. 4.6).

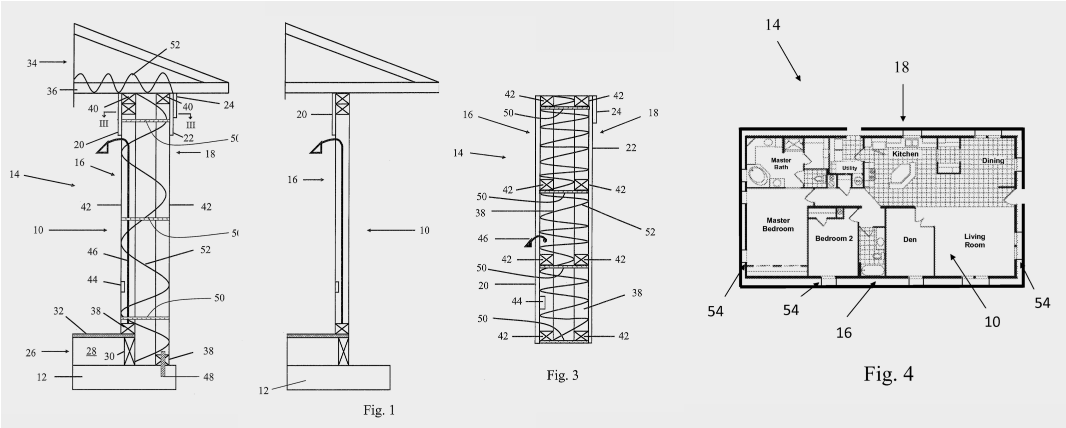


Fig. 4.5 Bentley Double Wall patent, 1976 USA (Bentley 1976)

In 1974 Richard Bentley submitted a patent for the double wall house (1974) (Figs. 4.5, 4.8), featuring air-tightness and air-to-air heat exchangers. The structure's design had an insulated double wall construction, with a minimum of connecting elements between interior and exterior wall surfaces, minimising thermal bridging. The ventilation system used a counter-flow heat exchanger for recovery of ventilated air that claimed to deliver 85% thermal heat demand reductions (Bentley 1974)[324].

4.4.6 Lo-Cal House (1976)

Schick's Lo-Cal House (1976) featured high levels of thermal insulation, airtight construction and heat recovery ventilation, using air-to-air heat exchangers and optimal solar orientations. The design, which features very similar details to contemporary passive house (Fig. 4.7), included 0.17 W/m^2K roof, 0.03 W/m^2K walls, 0.07 W/m^2K floor and triple glazed windows (0.37 W/m^2K). The design optimised window openings on the south face (85%) and minimised openings on the other aspects, to minimise heat loss. The very low window performance was complimented with 0.82 shading factor, maximising solar radiation gain in winter. The roof overhang (760mm) minimised overheating from solar gain in summer. Air-tightness was targeted at 0.5 air changes per hour (1 ACH recorded on study buildings). Schick and his team also carried out computer modelling for shading using deciduous trees to the east, south and west of the house.

The *Lo-Cal House* used a polyethylene vapour retarder (barrier) on all exposed surfaces and a whole house 0.5 air change per hour, with ventilation dependent on manually opening windows. The design included one fixed forced-ventilation point for supply and return, including switch-operated forced-ventilation of kitchen and bathrooms. This would raise concerns with the capacity for adequate ventilation of moisture without mechanical assistance. Builders of the houses recommended that the airtight barrier to the ceiling be omitted to allow moisture to wick through to the ventilated attic space (Schick 1979). The solution is very close to the passive house principles and detailing (Fig. 4.7), without the use of augmented whole house mechanical assisted ventilation and thermal bridge-free construction (Passive House Institute 2011)[325]. About 100 Lo-Cal houses were ultimately built. Schick coined the term "super-insulation" for the well-insulated constructions (Shick 1979.). The authors published a detailed energy performance in 1979. [326]

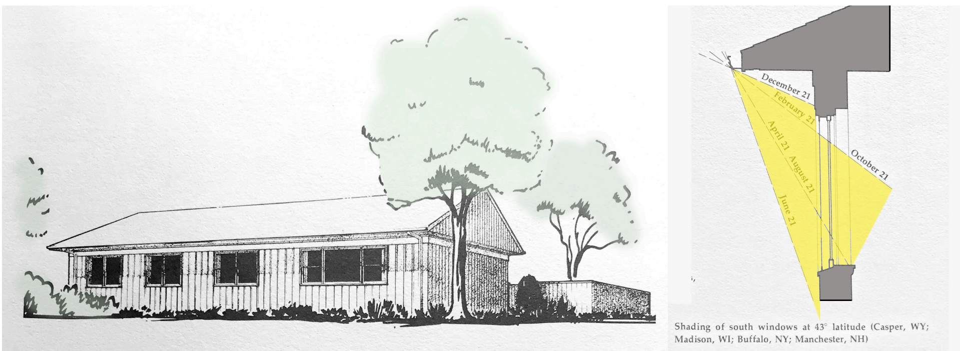


Fig. 4.6 Lo-Cal House, University of Illinois, 1976 USA (Lee 1977)

4.4.7 Twin Rivers Retrofit (1976)

In 1977, the Princeton House Doctors were carrying out studies on the loft insulation of two existing houses in New Jersey, when they discovered performance gaps between predictive models and actual energy consumption post-occupancy (Holladay 2015)[327]. This led to the discovery of *thermal bypass* or *thermal bridging*, by Gautam Dutt of Princeton University's Centre for Energy and Environmental Studies (Socolow 1991)[328], which, he concluded, was "responsible for the loss of about 35 percent of the energy released in a Twin Rivers townhouse during cold months" (Socolow 1991). With the first example of retrofit, the houses achieved an 86% home heating efficiency over the average US house in 1978 (Flavin 1980)[329].

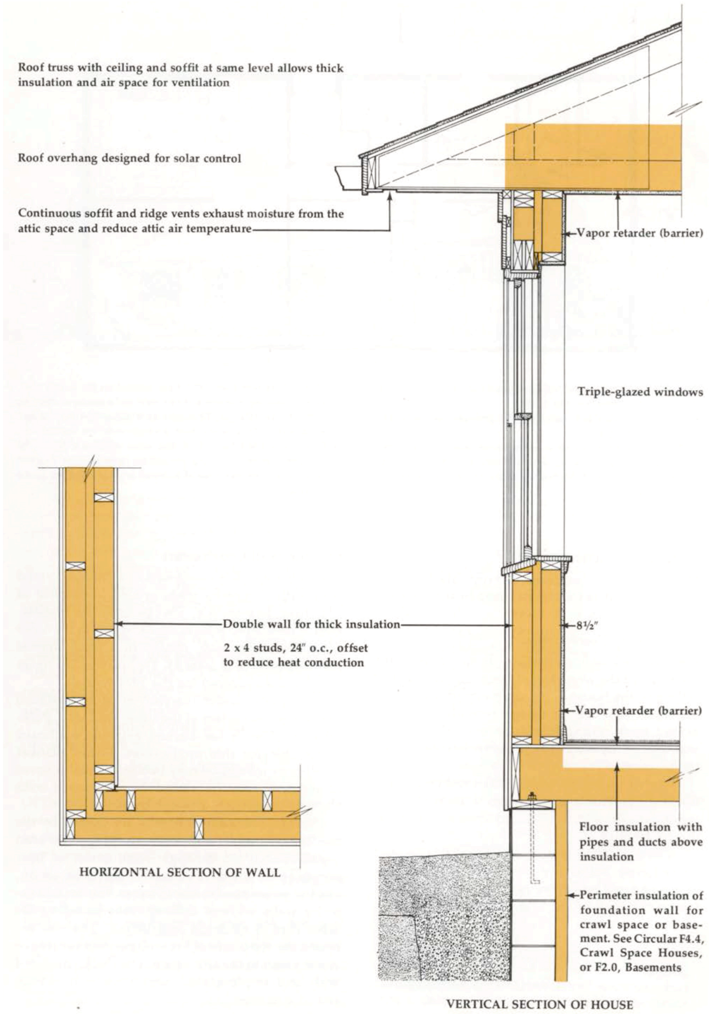


Fig. 4.7 Schick and Konzo Lo-Cal House 1976, WALL SECTIONS. These illustrations are very close to passive house details in 2016

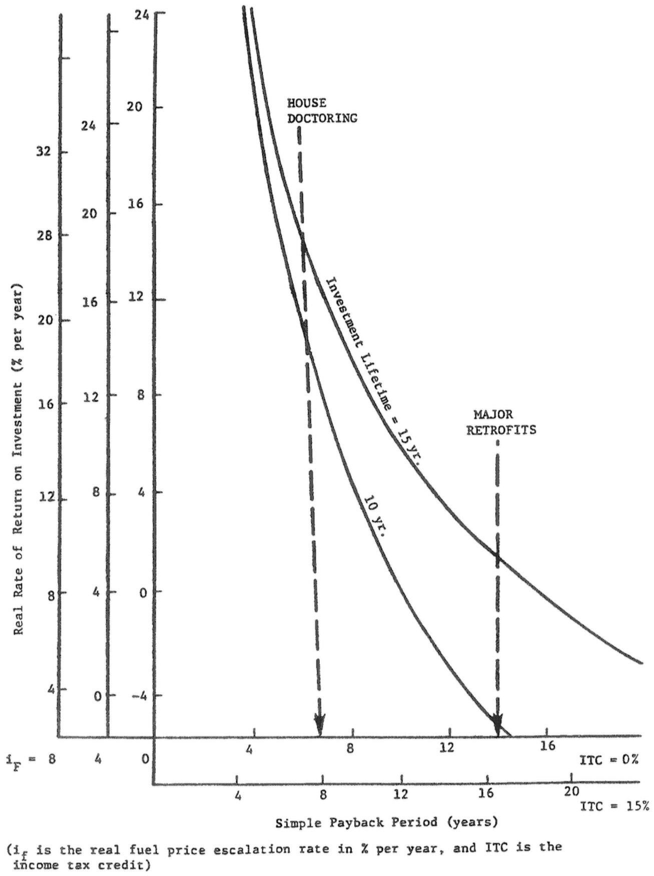


Fig. 4.8 Princeton House Doctors, Rate of Return on analysis (1982)

Identifying the role of thermal bridging in envelope heat loss would help close the gap towards what would become the Passive House principles, which are outlined as:

- Good levels of insulation with minimal thermal bridges,
- Passive solar gains and internal heat sources,
- Excellent level of air-tightness,
- Good indoor air quality, provided by a whole-house mechanical ventilation system, with highly efficient heat recovery.

The Twin Rivers retrofits to 7 separate houses were among the first examples of low-energy housing to tackle payback scenarios for RoI and to identify that oil price inflation was a relevant factor. “The rate of return depends on the real fuel price escalation rate (for) the retrofit lifetime, the simple payback period and whether or not there is a 15% income tax credit for retrofit expenditure” (Lavine and Socolow 1982)[330].

4.4.7 Canada (1977)

Fig. 4.9 Saskatchewan Conservation House, Canada (1977)

The Saskatchewan Conservation House by William Shurcliff, Dave Eyre, Bob Besant, Rob Dumont and Harold Orr used many of the same principles as the Zero Energy House (Denmark 1974)[331], the Lo-Cal House and Bentley's Double wall (Henry 2012)[332](Hernandez and Kenny 2010)[333], further developing the concept of active solar housing with super-insulation. The design was a direct development of the active solar precedents of the Zero Energy House, Copenhagen (Besant, Dumont and Schoenau 1979).

	M.I.T. Solar I Cambridge, Mass. 1939 - 41	Zero-energy house Denmark 1975	Provident house Toronto 1976	Saskatchewan Conservation House Regina 1977
Heated floor-area (m^2)	46.5	120	325	188
Solar-collector area (m^2)	33.5	42.0	66.6	17.9
Collector type	water, flat plate 3 glazings non-selective	water, flat plate 2 glazings non-selective	water, flat plate single glazing selective surface	antifreeze evacuated tube selective surface
Collector tilt angle	latitude —12°	latitude +34°	latitude +12°	latitude +20°
Collector area/floor area	0.72	0.35	0.20	0.10
Water-storage volume (litres)	79,000 steel tank	30,000 steel tank	272,000 concrete tank	12,700 steel tank
Waterstorage volume/house volume	0.71	0.10	0.35	0.028
Annual solar radiation on horizontal surface $\frac{\text{Gigajoules}}{m^2}$	5.0	3.5	5.0	5.1
Latitude	42° 20'	55° 41'	43° 40'	50° 30'
Annual degree days (°C-Days) (reference 18.3 °C)	3,130	3,738	3,793	6,003
Thermal resistance values (m^2 °C/W)				
Ceilings	2.6 (R15)	9.2 (R52)	7.0 (R40)	10.6 (R60)
Walls	2.1 (R12)	6.9 (R39)	4.9 (R28)	7.3 (R41)
House heat-loss coefficient (W/°C) heat-loss rate per unit temp. diff. between outside and inside	108	119 shutters open 75 shutters closed	227	99 shutters open 68 shutters closed
Insulating window shutters	no	yes	no	yes
Air-to-air heat exchanger	no	yes	yes	yes
Waste-water heat exchanger	no	yes	no	yes

Table 4.6 Active Solar system, 100% space heated houses (Besant, Dumont and Schoenau 1979, p165)

The design, which was commissioned by the Provincial Government (Ecohome 2013)[334], used "double-wall construction" (Flavin 1980)[335], with "R40 walls, R60 attic, triple glazed windows or windows with shutters, no basement, a crawl space with R20 in the floor system, and a very tight air / vapour barrier" (Ecohome 2013)[336]. Orr believed that greater demand-side space heating savings could be made by "reducing air leakage by 80% and heat loss to ground (basement) by about 80%; we would have a 64% reduction in heat loss without touching the windows and doors, walls, and ceiling. If we use 6 times as much insulation in the walls and ceiling and use much better windows and doors, we would be down to a total heat loss that is about 20% of the heat loss of a conventional house" (Orr 2013)[337]. By focusing on conservation or passive aspects first, Orr and the team realised that "conservation is much less expensive than solar. For every dollar we spent on reducing heat loss from the house, with a better air barrier and more insulation, we saved at least $10 on the size of solar collectors and equipment needed to achieve the same thing." (Orr 2013)[338].

Orr started to underline the financial reasoning for the super-insulated envelope. He also identified that building a double wall was cheaper than cross-battening the interior of the external wall, and that blown mineral fibre was much cheaper than rigid insulation. Having identified the potential to locate the vapour barrier on the outside of the internal wall, thus avoiding potential services clashes, the vapour barrier ended up on the room side of the internal wall creating difficult service interfaces. The construction still achieved 0.8 Air changes at 50 Pascals. The house layout with the living accommodations facing south and utility accommodations to the north, with most of the windows facing south, shading devices, heat exchanger and super-insulation would influence Wolfgang Feist's principles of *Passive House* in 1988.

Feist said, "At the time we knew about other similar buildings — buildings made by William Schurcliff and Harold Orr — and we relied on these ideas" (Holladay 2015)[339]. The Saskatchewan house was well documented and would become a precedent for Home World (1981) and Energy World (1986) in the UK.

Annual Home Heating Costs According to Different Building Standards*

Structure or Standard	Annual Cost (dollars)
U.S. average house, 1978	680
French building code, 1974	500
U.S. building standards, 1978	360
Swedish building code, 1977	230
California building code, 1979	220
Town house with retrofit, Twin Rivers, New Jersey	95
Saskatchewan Conservation House	20
Village House I, passive solar	15

*Assumes similarly sized houses using oil heat in a similar climate.
Source: A. H. Rosenfeld *et al.*

Table 4.5 Annual Home Heating Costs, 1978 (Flavin1980)[340]

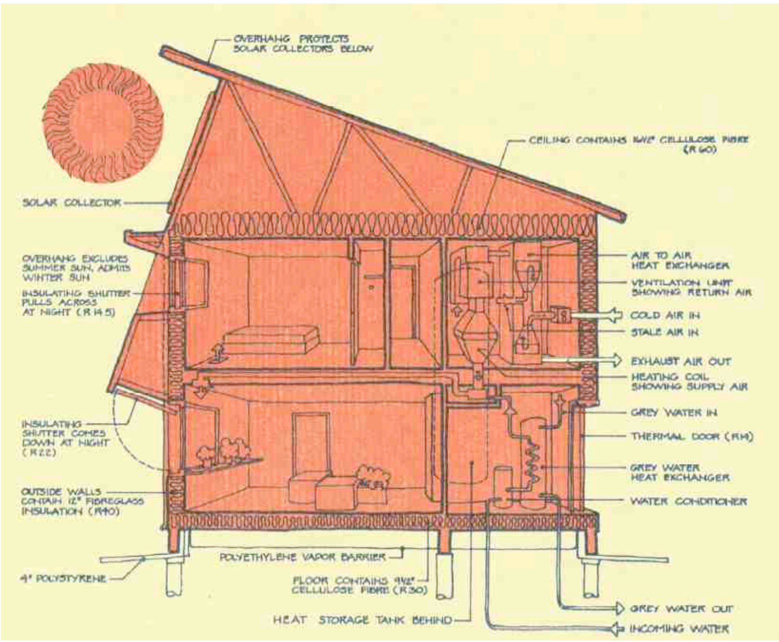


Fig. 4.10 Saskatchewan Conservation House section, Canada (1977)

The developments in Denmark, Germany, the US and Canada would help inform low-energy design solutions thereafter. Although the early documented exemplars are all residential applications, they still establish the principal of energy demand reduction first. Even the Phillips House, which was intended to test active systems, found that demand reductions through envelope insulation were more efficient than some of the active systems. There are a number of emergent commercial buildings from this time frame worth noting: Madeira School Science Building (1975, Greenwat Virginia, Active Solar), Mohansen Central School retrofit (1975, Schenectady, New York, façade insulation) (Fig. 4.11), Philadelphia United Fund Building (1971, Philadelphia, double skin façade). There is, however, little published evidence of energy efficiencies on these projects.

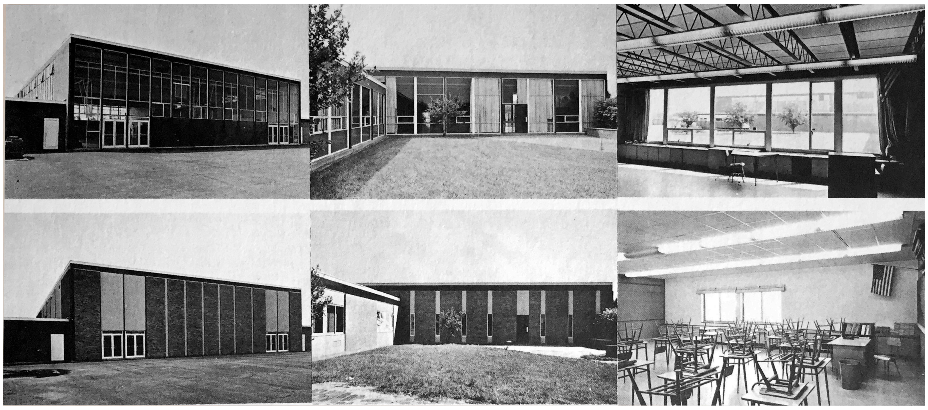


Fig. 4.11 Mohansen Central School retrofit (1975, Schenectady, New York) (Lee, 1977)

4.5 Legislative implements post-oil crisis

This part of the contextual domain examines the legislative actions taken primarily in the US, UK and Ireland in the wake of the 1973-74 oil crisis, to establish their impact on promoting energy conservation in building design.

4.5.1 UK legislative actions on energy

In 1965 the UK introduced building regulations, which were revised in 1972 and updated after the first oil crisis (Killip 2005)[341]. Few Irish regulations existed in the early 1970s, except for municipal bylaws, and many commercial design teams looked to the UK for good practice guidance (Burgess 2014)[342]. This would be mirrored in the design of the Regional Technical Colleges in 1968, where the design team looked both to UK regulations and UK Ministry of Education standards in terms of investment and quality. In 1966/67 there was little emphasis on energy conservation, with relatively high U-Values for walls and roofs, requiring little, if any, insulation (depending on wall build-up). This, perhaps, illustrates the low priority attributed to energy conservation in legislative and architectural practice prior to the first oil crisis.

UK policy in reaction to the first oil crisis, much like the US, was to establish a Ministry of Energy from the former Department of Trade and Industry (DTI) (Merrill 2007)[343]. The UK government took steps in 1976 to seriously revise the standard elemental U-Values of the building regulations, but these would be nowhere near the standards of the Philips experimental House (1974) or the Copenhagen Zero Energy House (1975) (Table 4.8).

Progression of UK-Energy regulations 1965-2010								
YEAR	1965	1976	1985	1990	1995	2002	2006	2010
FABRIC	U-Value W/m2.K							
Walls	1.7	1	0.6	0.45	0.45	0.35	0.35	0.35
Floors		1	0.6	0.45	0.45	0.25	0.25	0.25
Pitched Roof	1.4	0.6	0.35	0.25	0.25	0.25	0.25	0.25
Flat Roof		0.6	0.35	0.25	0.25	0.16	0.25	0.25
Windows metal						2.2	2.2	2.2
Windows all other						2	2.2	2.2
Window Area				15%	22.50%	25%		
Pedestrian Door							2.2	
Vehicle Doors							1.5	1.5
Entrance Doors							6	3.5
Air Permeability3							10	
Notes 1. 2006 values are area-weighted average limiting standards (Part L2A). SBEM calculation required. 2. 2010 values are limiting fabric parameters (Part L2A). SBEM calculation required. 3. Air permeability units m3/(h.m2) @ 50Pa.								

Table 4.8 UK U-Value progressions in regulations (Ó'Riain 2016)[344]

UK policy, much like the US, focused on energy independence and the expansion of internal supply. Alternative energy research was carried out by the newly formed Energy Technology Support Unit (ETSU), which was established in April 1974, following the US Energy Summit in February (Wilson 2010)[345]. The ETSU report *Energy 1974, And After* outlined a coal, energy conservation and nuclear (CoCoNuke) route to energy security for Britain[346]. Table 4.9 demonstrates an increase in both gas and nuclear energy and a reduction in oil consumption post-oil crisis 1973/74. The UK dramatically increased its exploitation of North Sea oil in 1975 to the mid-1980s, moving its oil consumption to indigenous supply (UK National Archives 2007)[347]. The Irish government at the same time did not have indigenous oil, nuclear or gas production, and were dependent on indigenous fossil fuels like peat and coal, as well as a significant proportion of imported fuels like oil (Flynn 2007).

UK Primary Energy Consumption, 1965-1975 (Mtoe)

	1965	1970	1971	1972	1973	1974	1975
Oil	74.2	103.6	104.3	110.5	113.2	105.3	92.0
Coal	117.4	96.0	85.1	74.5	80.7	71.1	71.5
Natural Gas	0.7	10.2	16.4	23.3	25.2	30.1	31.6
Nuclear	3.4	5.9	6.2	6.6	6.3	7.6	8.2
Hydro	1.1	1.3	1.0	1.0	1.0	1.1	1.1
Total consumption	**196.8**	**216.9**	**213.0**	**216.0**	**226.5**	**215.1**	**203.1**

Table 4.9 BP, Statistical Review of World Energy 2007

Solar, wind, geothermal and wave energy were seen by the UK Government in 1974 as “economically highly unattractive”, even though Chapman et al. (1974)[348] recognised the “climatic effects of heat release” in processing fossil fuels in 1974. Their view was that ”serious consideration should therefore be given to “deflationary” technologies such as increased materials recycling and increased development of the use of renewable energy sources“[349], but this view would not hold sway in policymaking.

In 1974 the UK Department of the Environment made insulation materials and their installation free of charge to private insulation contractors, through grants for energy retrofit. “Over 5,000 houses were improved in this way, the average cost of installation being £50 per house” (Fuller, Doggart and Everett 1982)[350]. Although there was an investment in energy conservation measures and renewable energy, the development of the technologies was so early that they would only play a minor role in the energy mix and policy solutions in the 1970s.

In 1977 the Irish government would introduce a fuel allowance (Gallagher 1995)[351], which would do little to address energy conservation. The UK introduced the *Home Insulation Scheme* (1978) as part of an energy conservation program announced in 1977 (Benn 1977)[352]. The scheme promoted attic insulation and draught proofing, with a 45% take up of grants in England (Atherton 1980)[353]. From 1980-1982 and 1985-87 the Irish government introduced a similar grant for attic insulation to improve 88,000 Irish homes or 10% of the total dwellings (Gallagher 1995).

The late 1970s in the UK was marked by much industrial unrest, which leads to the *Winter of Discontent* in 1978/79. When Margaret Thatcher was elected as leader of the Conservative government in May 1979, she set out to "break the power of the National Union of Mineworkers (and other unions), who "hold the country to ransom", and radically change an inefficient public sector monopoly, through transforming the industry into a viable private enterprise" (Pearson and Watson 2010)[354]. She moved policy towards the expansion of the nuclear industry after the second oil crisis (1979), which would see the domestic coal industry dismantled by 1990 (Pearson and Watson 2010).

A second oil crisis hit in 1979, with the UK instituting an immediate target for a 5% cut in oil consumption, in conjunction with IEA targets. As part of the plan, the UK aimed to bring 5.6 million homes up to a minimum standard of insulation over a 10-year period, but comments by the Ministry for Energy on its *Energy 33* report (1979) admitted that "progress was slow" and the government were not setting a good example to the public. They proposed that legislation was needed to encourage energy conservation measures, citing a largely voluntary energy policy to date, and that only at times of an energy crisis was there a political disposition towards compulsory energy conservation measures. In the

Energy 33 report, there was one energy conservation measure recommended, the inclusion of heating controls in building regulations. Also, “serious consideration (was given to) whether building controls could be abolished”, and if a greater investment in solar technology could be made (UK Department of Energy 1979)[355]. Interestingly, UK policy in the wake of the first oil crisis moved towards energy independence, resulting in a shifting of public opinion away from energy conservation: “The UK’s fortunate position as an oil producer approaching self-sufficiency, creates a climate of opinion unsympathetic to the idea of mandatory restrictions on the use of energy…. whilst the cutback in world oil supplies as a result of the Iranian crisis has, however, sharply underlined the need to save energy” (UK Interdepartmental Official committee on Energy conservation 1979)[356]. Energy 33 found that people did not want the government interfering with the liberty of the individual in their own home (UK Department of Energy 1979)[357]. The report would recommend the maintenance of voluntary energy conservation measures.

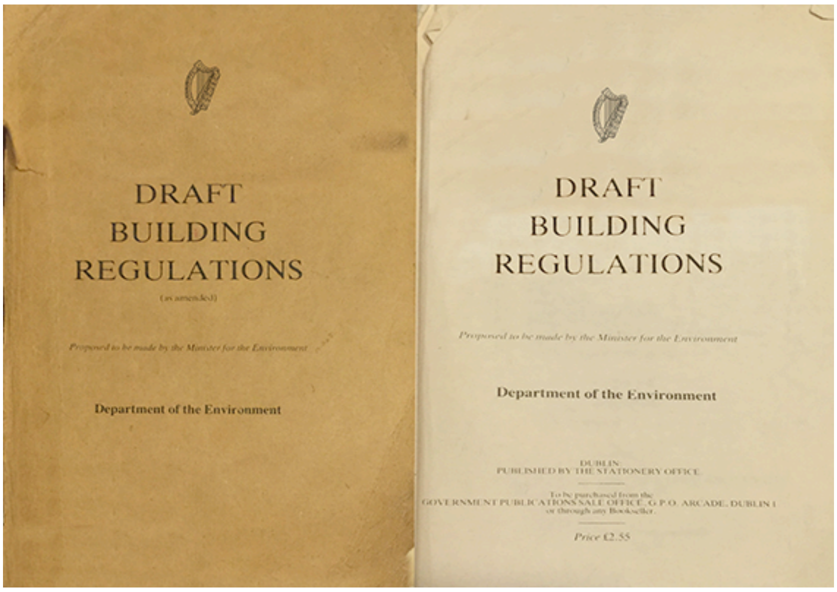


Fig. 4.12 Irish Draft Regulations 1976

4.5.2 Irish legislative actions on energy

The post-colonial Republic of Ireland had inherited much of its laws from its former ruler, Great Britain. As a result, laws were quite similar. However, up to 1963 there was no requirement for planning permission for development, but there were local bylaws in certain cities and towns. The 1963 Planning Act introduced controlled development and it intended to introduce building regulations. The UK, by contrast, had town-planning acts since 1909, with the Town and County Planning Act 1957 controlling both new builds and extensions (Forster 2013)[358].

In 1963, Ireland introduced a planning and development bill to law, the Local Government (Planning and Development) Act, 1963[359]. In Part 8 Section 86 it allowed for the introduction of building regulations to create basic standards for construction, which was not enacted until 1991. In the wake of the first oil crisis, Ireland brought out draft building guidance in 1976[360] (Fig. 4.12), which would be further revised in draft format in 1981 (Corrado 2012)[361]. The draft regulations introduced an elective benchmark, in terms of expected building performance criteria, with baseline values for thermal insulation (Table 4.10). Existing UK regulations for the insulation of buildings (Part F, 1972) were also revised in 1976 (Table 4.11) (Killip 2005)[362]. By contrast, the Irish U-Values (Table 4.2) were more onerous than the UK regulations (Table 4.3), but critically, not mandatory. Mandatory Irish building regulations were not enforced until 1992.

Fig. 4.13 Stardust Fire, Dublin 1981 (O'Connell 2009)[363]

Driving the introduction of these regulations was a disastrous fire that swept through a nightclub called *Stardust*, in North Dublin, in February 1981. Forty-eight people were killed and one hundred and twenty-eight seriously injured (Stardust Tribunal 1982)[364](Fig. 4.13). The political fallout from the Stardust Disaster highlighted the lack of building control, despite the existence of legislation dating back to the Local Government (Planning and Development) Act, 1963. Again, an exogenous event, rather than an environmental lobby, would prompt legislative change. The political fallout from the Stardust tragedy resulted in the passing of the Fire Services Bill, 1981 and an amendment to the 1976 Draft Building Regulations (which were not enforceable) in 1982, following the report on the Stardust Fire.

TABLE

Element of the building (1)	Maximum U value of any part of the element in W/m²°C (2)
1. External wall	0·60
2. Wall between a dwelling and another building which is not a dwelling	0·60
3. Wall between a dwelling and a ventilated space	0·60
4. Wall between a dwelling and an internal space ..	1·10
5. Wall or partition between a room and a roof space including that space and the roof over that space ..	0·60
6. External wall adjacent to a roof space over a dwelling including that space and any ceiling below that space ..	0·60
7. Floor between a dwelling and the external air ..	0·60
8. Floor between a dwelling and a ventilated space ..	0·60
9. Roof, including any ceiling to the roof, any roof space and any ceiling below that space	0·40

Table 4.10 Draft Irish Building Regulations 1976, U-Value table (The Department of the Environment 1976).

These were elective, non-mandatory standards in 1976, and more onerous than the UK regulations, but noticeably similar in structure and description.

Table to Regulation F3

Maximum U value of walls, floors and roofs **Fig 166**

Element of building (1)	Maximum U value of any part of element (in W/m²°C) (2)
1 External wall	1.0
2. Wall between a dwelling and a ventilated space	1.0
3. Wall between a dwelling and a partially ventilated space	1.7
4. Wall between a dwelling and any part of an adjoining building to which Part F is not applicable	1.7
5. Wall or partition between a room and a roof space, including that space and the roof over that space	1.0
6. External wall adjacent to a roof space over a dwelling, including that space and any ceiling below that space	1.0
7. Floor between a dwelling and the external air	1.0
8. Floor between a dwelling and a ventilated space	1.0
9. Roof. including any ceiling to the roof or any roof space and any ceiling below that space	0.6

Table 4.11 UK Building Regulations 1976, U -Value table (Stephenson 1978)[365].

The structure is remarkably similar to the Irish non-mandatory regulations. The 1976 review of UK 1965 standards had brought wall U-Values from 1.7 to 1.0. It would not be until 1985 that they would drop to 0.6.

4.6 US legislative actions on energy: A changing policy

In January 1979, the Shah of Iran was deposed and Iran ceased exporting oil, resulting in a second oil crisis in one decade, which would see oil prices peak at the equivalent of $117 per barrel (Fig. 4.2). Although Carter, as one of the last acts of his presidency, "sign[ed] the Energy Security Act, consisting of six major acts: U.S. Synthetic Fuels Corporation Act, Biomass Energy and Alcohol Fuels Act, Renewable Energy Resources Act, Solar Energy and Energy Conservation Act and Solar Energy and Energy

Conservation Bank Act, Geothermal Energy Act, and Ocean Thermal Energy Conversion Act"[366], the new Republican US president, in 1981, moved public policy away from fuel conservation and back to increasing domestic production. "Conservation, of course, is a most helpful thing, and we should be practicing it, but I truly believe the answer to our energy problem is an energetic program of increasing our own supply, and this we have not done" (Reagan 1979)[367]. Reagan quietly dismantled the solar panels on the White House (Fig. 4.14), with a chief of staff referring to them as "a joke" (Reagan 1979)[368]. He believed the market would be the answer to the energy problem and set out to "end oil price controls and to dismantle the cumbersome regulatory apparatus associated with those controls" (Reagan 1981)[369]. Regan rolled back legislation requiring mandatory product energy labelling, mandatory federal Building Energy Performance Standards and funding for schemes promoting minimum energy performance standards in new homes in 1981 (Gibbons 1992)[370].

Over the next 5 years, US policy featured deregulation, the dismantling of the Department of Energy, lifting the ban on the commercial reprocessing of nuclear waste, the creation of a 250 million oil barrel reserve and a major expansion of interstate gas pipelines. "Crude oil prices plummeted, falling below $10 per barrel by mid-1986" (WTRG Economics 2016)[371]. Reagan's position undermined the fledging renewable sector, seeing many solar industries going out of business, as solar power proved economically unsustainable in a cheap oil market. Market demand for low-energy buildings also decreased as oil prices fell (Steinmüller 2008).

Fig. 4.14 Jimmy Carter announcing solar panels on the White House (Pure Energies 2016)[372]

4.7 Low-Energy pilot-project s of the 1980s

4.7.1 UK (1981-86)

The Home World houses of 1981, developed by the government agency, exemplify early low-energy buildings in the UK. Milton Keynes Development Corporation was responsible for planning and developing the new city, which established an Energy Consultative Unit in 1976 (Fuller, Doggart and Everett 1982)[373]. They developed 52 low-energy houses at Pennyland and Great Linford, as part of an "applied test bed" for UK policy in energy conservation in residential buildings, which were exhibited at 'Home World' in 1981. They focused on:

1. Improving levels of insulation in new and existing buildings, particularly housing, and reducing energy losses in as many ways as possible.
2. Improving heating control systems in offices, factories and houses, and improving the efficiency of boilers.
3. Increasing the use of "free" solar energy in buildings to substitute for energy that at the moment has to be bought
   (Fuller, Doggart and Everett 1982)

Interestingly, they published payback periods for a number of energy strategies (Table 4.13) in which they did note that it was based on concurrent oil prices remaining static at over $90 per barrel. However, oil prices had peaked at $115 per barrel in 1980 and fell to $10 per barrel in 1986 (Table 4.12).

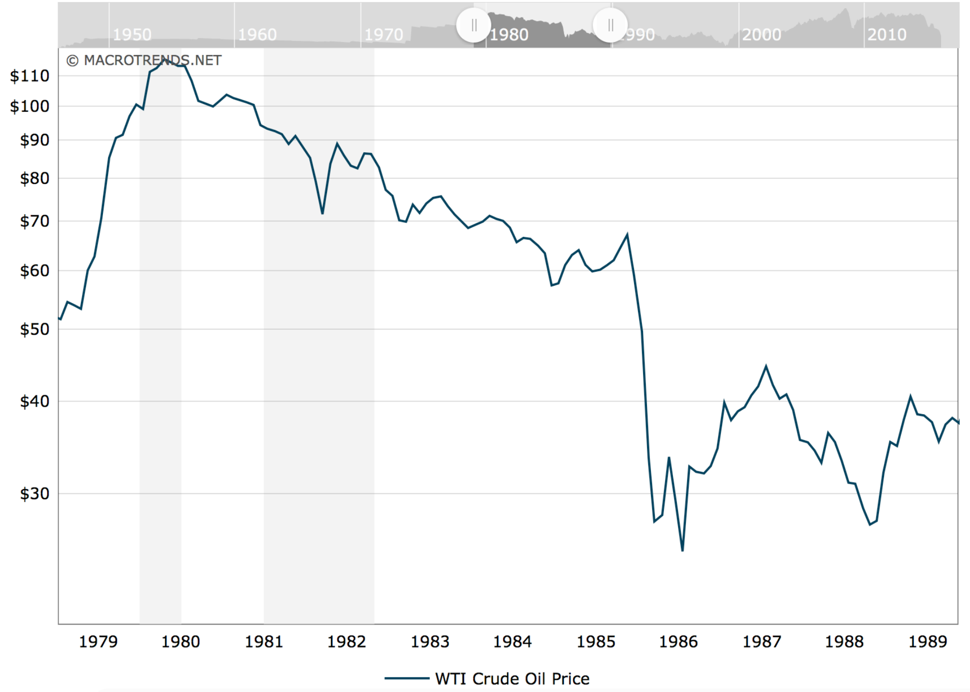


Table 4.12 Inflation-adjusted oil prices1979 - 1990 (Macro trends 2016)[374]

The first use of economic efficiency evaluations for low-energy buildings in Europe illustrated the need for sensitivity analysis for different future fuel cost scenarios. In 1982 Fuller et al. concluded that improved levels of insulation would have immediate returns, and that CHP and heat pumps had potential for further development and immediate savings[375]. The 1982 report found that active solar heating systems for houses were not cost-effective at that point in time. Even at a time of high oil prices, the active solar systems were not cost-effective in a UK climate context. This would seem to support Orr's findings (Orr 2013) on the competitiveness of energy conservation measures over active systems. Home World demonstrated the application of low-energy building design principles in a UK context. The University College of London found that insulation, fabric and orientation were more important than complex, renewable technologies and services that would have less of a lifespan than building fabric (BRE Global 2014)[376]. This is an important consideration in building retrofit, which is expanded upon in Chapter 5.

The Home World Exhibition (1981), and subsequent Energy World Exhibition (1985) in Milton Keynes, piloted low-energy houses based on a variety of precedents from Canada, Denmark, Sweden and New Zealand, which were at least 30% lower than concurrent regulations (Adam-Smith 2014)[377]. The various designs featured aspects of the Phillips Experimental House (Aachen 1975), with ventilation heat recovery systems, solar power, south-oriented triple glazing, heat pumps (Fig. 4.15), thermal mass to shift the Diurnal heat cycle and super-insulation (Byrne 2011)[378].

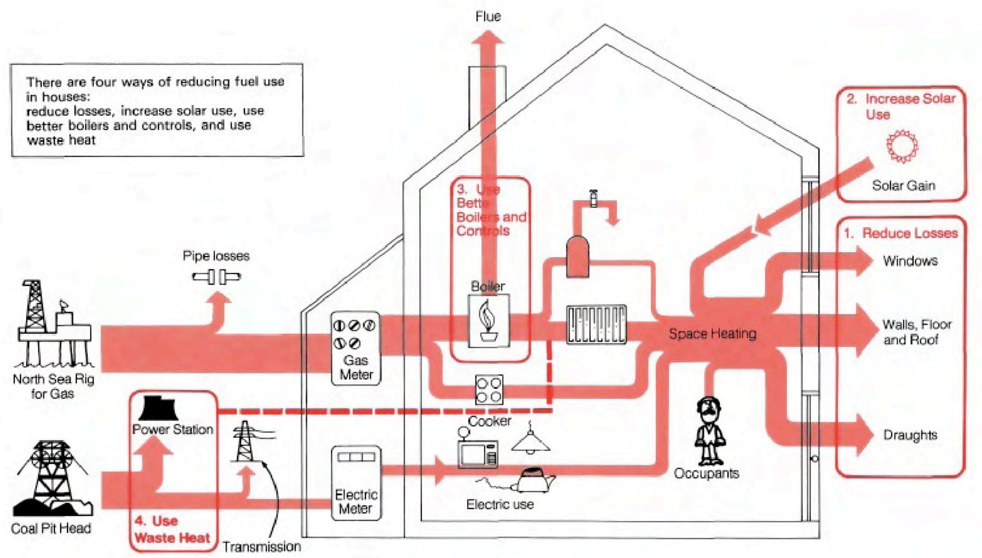


Fig. 4.15 Energy supplies and use in an average house. Ways of reducing fuel use. (Fuller et al. 1982)

In 1986 a follow-up demonstration, called Energy World, featured 51 low-energy houses with an energy rating, for the first time (Adam-Smith 2014). The Ideal Home Solar House (1986) (Fig. 4.16 right) was "radical in its look as well as its performance, a triple-glazed conservatory on the south side acts as a solar trap while the garage and porch on the north side act as a thermal buffer preventing heat loss through the exterior

(Adam-Smith 2014). The design was developed from the original Lorriman house (1976) in Ontario, Canada.

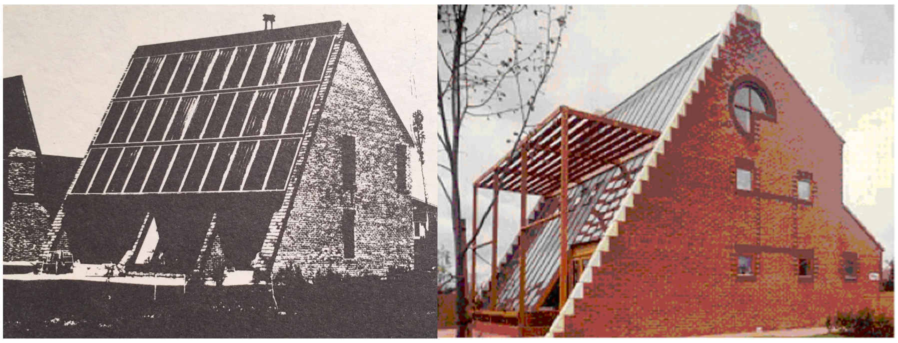


Fig. 4.16 Home World low-energy house 1981, Milton Keynes,
Designed by: Dominic Michaelis Associates, Built by: Abbey Homesteads

All its main rooms face south. The kitchen, dining and living areas have a quarry-tiled floor, which collects heat during the day, preventing overheating, and then gives off that heat in the early evening as the room temperature falls. There is also a chemical heat store and solar panel array.[379] The design of the Solar House can be compared closely with the design of Saskatchewan Conservation House: accommodations, building form, and orientation are all similar. Energy World was the first to introduce energy ratings for housing performance. Indeed, the National Energy Foundation was developed directly out of the Milton Keynes Energy Consultative Unit, which went on to develop the (UK) National Energy rating system in 1990 (Adam-Smith 2014)[380]. "It represented a milestone in the design and construction of energy efficient buildings and important developments in the evaluation of whole-house energy calculation procedures, now incorporated in the BREDEM (BRE Domestic Energy Model)" (Kelly, Crawford-Brown and Pollitt 2012)[381]. The UK's Standard Assessment Procedure (SAP) is a methodology for assessing "energy and environmental performance of dwellings… based on the BRE Domestic Energy Model (BREDEM). Reduced Data SAP (RdSAP 2005) is a lower cost method of assessing the energy performance of existing dwellings" (UK Department of Energy and Climate Change 2013)[382].

The payback calculations (Table 4.13), which were based on the relatively high 1981 prices, illustrate and reiterate the findings from the Saskatchewan House. Fabric insulation measures were 10-20 times more cost-efficient than active solar. It is key to understand that these calculations would be severely undermined by falling oil prices from 1981-1986.

Measures	Cost/House 1981 prices	Payback time against 1981 gas prices
DOMESTIC		
Insulation Kits		
— Extra loft insulation (25mm increased to 80mm), extra water cylinder jacket, and draught stripping	£70	2-4 yrs
Pennyland*		
— 50mm (2") cavity wall insulation, — 75mm (3") loft insulation	£100	5-10 yrs
— 100mm (4") cavity wall insulation, — 150mm (6") loft insulation and double glazing throughout	£500	10-20 yrs
Active Solar Heating		
— 4m^2 Thermosyphon solar water heater installed by resident	£300	20-30 yrs
— (with labour cost)	£600	50-60 yrs
— 40m^2 solar water and space heating system	£3,000	50-60 yrs

Measures	Cost/House 1981 prices	Payback time against 1981 gas prices
Gas-Fuelled Heat Pump		
— 150kW heat pump shared between 20 houses	£300	5-10 yrs
Mini-CHP Scheme		
— 1 Totem shared between 3 houses	£500	10-12 yrs
*A normal Pennyland house has: — no cavity wall insulation, 50mm (2") loft insulation, no double glazing		
INDUSTRIAL		
Better heating system controls		1yr
Draughtstripping and extra insulation		2-5 yrs
Large-scale solar water heating		10 yrs
SWIMMING POOLS (INDOOR)		
Heat Recovery Units		1-2 yrs
Pool covers		5 yrs
Solar Water Heating		10 yrs

Table 4.13

The following payback times assume that energy costs will not rise in real terms. In practice, however, it is very likely that they will increase, so the payback times may well be reduced. As indicated, the times are calculated against current gas prices. If the measures adopted reduce consumption of electricity, the payback times could be further reduced, by up to as much as a half.

Table 4.13 Payback times for energy saving measures. (Fuller, Doggart and Everett 1982)[383]

4.7.2 German and Swedish Super-low-energy houses (1986)

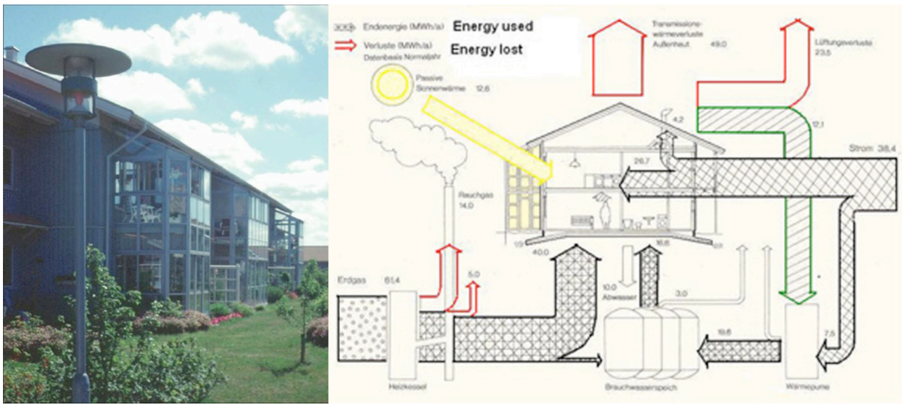


Fig. 4.17 Low-Energy Buildings in Germany (Ingolstadt) 1986 (Liebke et al. 1995)[384]

In 1986, Swedish researchers pioneered low-energy housing - in a more extreme climate than the UK - in Halmstadt (Sweden) and, in a similar environment, at Ingolstadt (Germany), developing houses with a high degree of air-tightness, super-insulation, high performance windows and mechanical ventilation heat recovery. The architect Hans Eek rejected an active "technological Christmas tree" approach (Glad 2008)[385]. Energy tests were made and occupants were interviewed from 1987 to 1990. "The effective energy consumption was found to amount to circa 50 kWh/m^2 annually, which is about half the consumption of a new conventional German building" (Liebke et al. 1995)[386]. The project effectively used Swedish building techniques with German heat pumps, at the same capital cost as a conventional German building.

The projects were based on super-insulated fabric, orientation and, as a first step, the remaining space heat demand was met by active systems such as heat pumps, heat exchangers and solar panels. Where these projects were monitored, weaknesses in window technology, thermal bridging and air-tightness were the principal problems. The lack of an adequate understanding of the impact of poor shading resulted in summer overheating; "they were draughty, not too comfortable, they cost far more to heat than predicted, and they frequently overheated during summer" (Rodell 2015)[387].

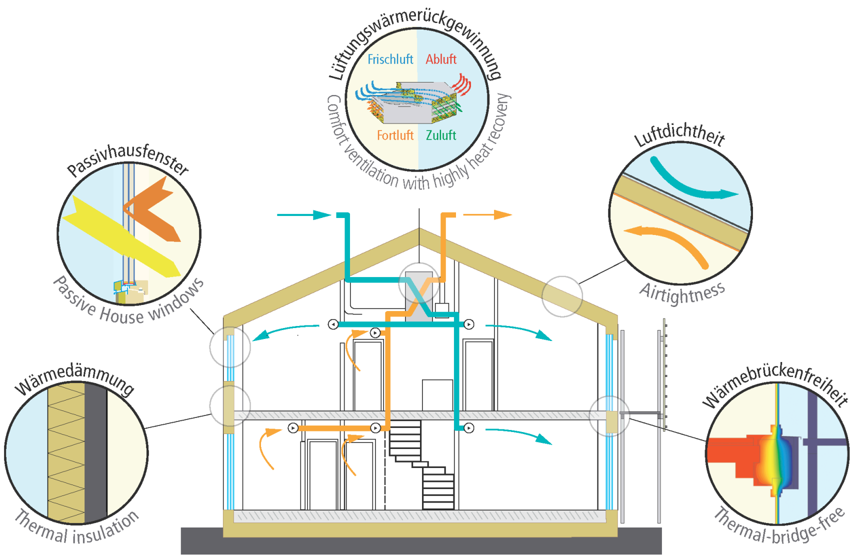


Fig. 4.19. *Passive House* design principles (Passive House Institute 2016)[388].

4.7.3 The Passive House Standard (1988)

Early passive (solar) houses optimally oriented buildings towards the sun, where the design of the building "is strongly related to the site, climate, local building materials and the sun…[with a focus on] passive solar heating and cooling systems" (Mazria, 1979)[389]. These buildings tended to use solar collectors with brine or water tanks in wall or buried in the ground to bank heat energy. As we have seen from various case studies, from the Copenhagen, Saskatchewan and Milton Keynes projects, seasonal thermal storage appears to be an expensive enterprise with a lot of heat loss.

The Phillips House 1975 and the Illinois Lo-cal houses (1976) both used heat pumps or active systems to supplement a super-insulated envelope. This could be referred to as augmented Passive House, which uses the principle of solar orientation with super insulation to reduce building energy demand by 80% and supplement the remaining demand with active systems such as heat pumps or mechanical ventilation heat recovery.

This is essentially what the PassivHaus standard would reflect, a primarily passive design augmented with active systems to minimise whole building energy demand.

Technical Definition:

"A Passive House is a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air… Thermal comfort is achieved to a maximum extent through passive measures (insulation, heat recovery, passive use of solar energy and internal heat sources)" Feist, 2016.[390]

The Passive House Standard would fill a research void left by low energy prices in the US and the UK from 1986-2002. Influenced by most of the low-energy precedents covered earlier, Passive House is perhaps one of the most important developments in low-energy building. Wolfgang Feist and Bo Adamson developed the Passive House Standard in 1988. The voluntary German building energy performance standard was primarily centred around passive solar heat gains, thermal comfort, super-insulation, air-tightness, mechanical ventilation heat recovery (although not exclusively), and thermal bridge-free construction (Kaan and Boer 2006)[391].

Supported by government subsidies, Bott, Ridder and Westermeyer Architects developed a 4-house terrace to the Passive House standard in 1990. The "Passive House Preparatory Research Project", as it was called, featured super-insulated fabric, insulated window frames, reduced thermal bridges and ventilation heat recovery, which has contributed to a performance of 10 kWh/(m^2a) in space heat demand from 1991-2014 (Passipedia 2015)[392]. The standard, which was based on the principle of energy demand reduction through a super-insulated airtight envelope, augmented by active systems to meet the remaining demand, set quantitative performance targets for designers to meet in order to achieve a very low whole-building energy performance. The system synthesised most of the previous passive strategies with MVHR, into a quantifiable design process. Interestingly, active solar (potentially due to cost) is not a core part of this strategy.

The system minimises heat loss by having a continuous insulation and air-tightness boundary layer. Commercial blower doors became available in 1980, allowing designers to test air-tightness to the Passive House standard ($0.6m^3/(m^2 \cdot h)$ @50 Pa). A Passive House building design optimises heating season passive solar heat gain through orientation of the main windows and rooms to the south, with utility rooms to the north. Similar to the Saskatchewan Conservation House, mechanical ventilation heat recovery (MVHR) is used to reduce heat loss and fresh air ventilation (operable windows) in cooling season (similar to the Phillips House). Designers must use high performance glazing ($<0.85W/m^2k$) (a similar strategy to the Lo-Cal House 1976) and achieve zero thermal bridging (identified at Twin Rivers) (Nisson and Dutt 1985)[393]. The standard requires shading devices to moderate summer overheating, employing natural shading such as deciduous trees or building integrated shading (similar to the Lo-Cal House 1976). The highly technical system is based on knowledge of building physics, a level of sophistication or specialisation not commonly found in architectural education (Tzonis 2014)[394], and as a result, not abundant in architectural practice. There are only 3000 certified passive house designers worldwide, with 323 in Ireland out of 2507 registered architects in 2016 (Maguire 2016)[395]. The standard, and its excel-based planning software, requires the building designer to become familiar with local climate conditions, mechanical systems, solar heat gain calculations, and thermal bridging calculations. The key energy performance standards are 15 kWh/m^2a for the heating and cooling load, with remaining loads attributable to lighting and plug loads, leaving a total overall building primary energy demand of 120 kWh/m^2a. The Passive House standard, thus, includes plug loads and is primarily focused on residential applications. This creates a problem, in that Passive House is not directly comparable with other standards, as it captures all the energy demands in a house. It creates another problem, in that occupant behaviour and differing markets can influence process load use. For example, average lighting and plug load usage in the US is 38% higher (6,600 kWh/person/year) than the median certified passive house allowance (4,100 kWh/person/year) (Wright, Klingenberg and Pettit 2014)[396]. Non-residential applications of Passive House must contend with different process load issues; different occupancy profiles and equipment densities will impact both process load demand and occupant/equipment related internal heat gains. Therefore, the design profile of a Passive House office or education building may be less reliant on heating season passive solar heat gains and more reliant on the moderation of overheating from internal gains in cooling season.

In 1996, an economical planning package was developed to demonstrate payback periods, based on unit costs of energy plus inflation (Passivhaus 2016)[397]. In 2006 the EU Action Plan for energy Efficieny called on the EU commission to adopt Passive House standards for all new non-dwellings from from 2011 (European comission 2006)[398]. The Passive House standard would continue to have a significant influence on EU legislation for Energy conservation in buildings thereafter. In 2011, Passive House introduced a relaxed standard for building retrofit, called EnerPHit. Whilst it relaxed standards for space heat demand (25 kWh/m^2a) and air-tightness (1 $m^3/(m^2 \cdot h)$ @50 Pa), the overall whole building performance remained the same (120 kWh/m^2a).

Passive House is the single most popular voluntary low-energy design process in the world, with an estimated 25,000 (as of 2011) certified Passive Houses built worldwide (Bell 2011)[399]. The weakness of the system is perhaps the need for so much training and the lack of intuitive design software. For architects, *Passive House* offers a measurable and quantifiable results-based matrix for design decision-making. It offers clear, if complex, strategies that can inform the design process.

Passive House would go on to certify passive house products such as high efficiency windows, doors, MHRV, heat exchangers and buffer tanks.

4.7.4 Green Building, Dublin (1994)

Supported by €3 million in European funding, Tim Cooper, with Murray Ó Laoire Architects, developed a design for the Green Building in Temple Bar, Dublin. It was "an innovative, mixed-use development of offices, apartments and shop units, laid out around a six-storey central courtyard designed as a semi-external atrium space, with a glazed, operable roof. The atrium's roof is oriented southwards and designed to naturally ventilate and light the building" (Walsh 2011)[400]. The building was designed with a low glazing factor and high interior radiant panel surfaces, supplied by low temperature solar water heating. The building benefitted from its compact apartment units' mid-terrace location, thus reducing surface heat loss. The envelope uses an external insulation, coupled with south facing double-glazed windows and triple glazing on the north face. Unlike the Swedish approach, the Green Building has an intensive use of active systems, with "solar panels, both photovoltaic and evacuated tube, wind turbines and a ground source heat pump". The PV energy production (3,000 kWh/a) meets 75% of associated heat pump electrical demand (4000 kWh/a). Although grid-connected, surplus electrical energy is fed back to the grid for free, as there is no associated purchase tariff. The architect, Cooper, reported: "When we first put them in (PV panels) we couldn't grid a connection, so we had to put in the massive accumulator and a stack of inverters. That is now all redundant. The grid-connected photovoltaic alone is much more efficient than the photovoltaic and turbines were together, before" (Walsh 2011). The wind turbine had proved a failure and was decommissioned. The vertical ground source heat pump runs at a very efficient 5:1 co-efficiency of performance. This first example, in Ireland, of low-energy building design had a blend of passive and active solutions. Of the active solutions, the PV and ground source heat pump would appear to function well with the internal thermal mass of the building fabric.

4.7.5 BedZED (1999-2002)

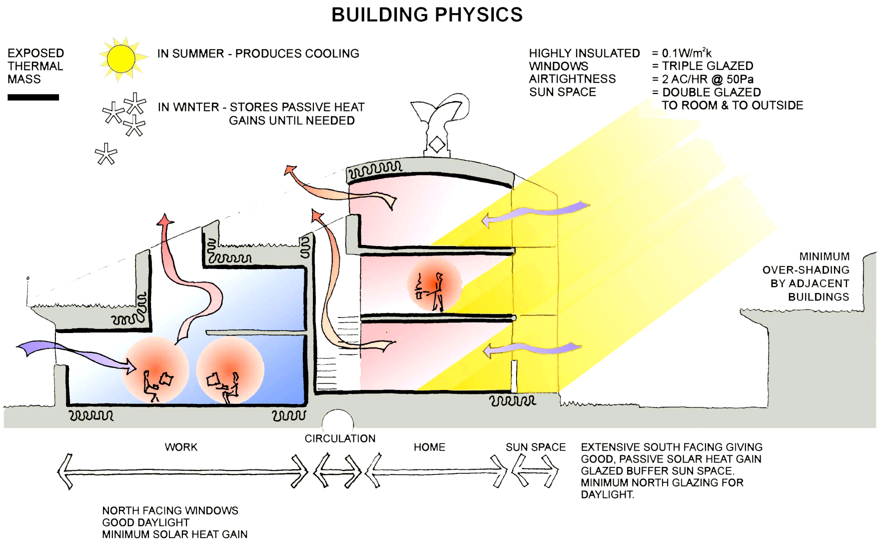


Fig. 4.20 BedZED Strategy, (Peabody Trust, 2014)[401]

Beddington Zero (fossil) Energy Development (BedZED) is mentioned here as a large community development, which followed on from other UK developments in the 1990s, such as Autonomous House 1994 in Southwell and Hockerton Housing Project in 1998, both by Brenda and Robert Vale in Nottinghamshire and based on the book *Autonomous House* 1975 (International Energy Agency 2015)[402]. All three projects use a super-insulated envelope, good air-tightness, triple-glazed windows, exposed internal thermal mass, passive solar heat gain and grid-connected photovoltaic panels (PV) (Fig. 4.20). In creating an exemplar demonstrating the application of technologies, much like Energy World, “Lovell (2009) suggested that BedZED has played an important role in persuading policy makers to set higher building energy standards, particularly because the physical presence of the new objects and technologies provides a tangible expression of potential policy outcomes” (Berry 2012)[403].

4.7.6 Low-energy buildings

The second wave of low-energy buildings of the 1980s and 1990s established some new ground in topic area. Developing from Twin-Rivers (1979) payback methods, Home World (1981) established elemental strategy payback periods, which demonstrated the relative efficiency of energy conservation through envelope insulation, over active systems, like solar water heating. However, the falling prices of oil would undermine these payback periods, making their wider market adoption unprofitable. Energy efficient buildings would remain an elective choice for a building owner. Exemplars like the Green Building in Dublin highlighted both systemic and technological issues with active systems.

4.8 Climate change agreements and the built environment (1990s)

Ireland eventually introduced mandatory building regulations in 1991, with U-Values the same as the 1976 draft regulation and less onerous than the UK counterparts. At the same time, the EU made a paradigm shift in environmental policy from a trade orientation to an environmental orientation (Scheuer 2014)[404]. This was due, in no small part, to the increase in environmental groups and the success of environmental policies at the ballot box, post-Chernobyl.

> ***"At the end of the 1980s, there was a mounting wave of environmentalism. Membership of environmental organisations increased considerably. Green parties were popular in several EU countries, and achieved good results at national level and in the European Parliament."***
> ***(Scheuer 2014)***

The pan-global realities of 1980s' cold war politics and Glasnost, would become the exogenous factors enabling international agreements on environmental issues. The international political community became pragmatically inclined towards environmental positions. The environment was now associated with freedom and democracy, one of the central themes and desires of the West (Scheuer 2014).

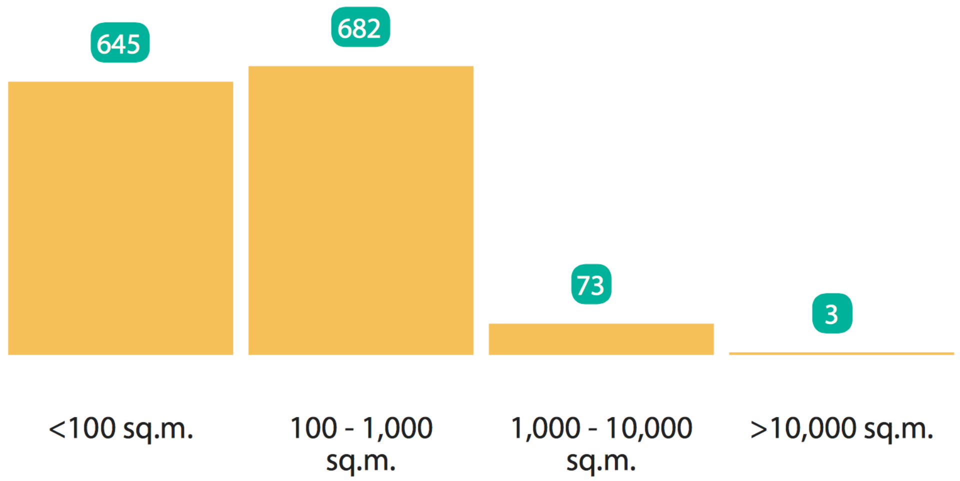
This movement led to the first UN Earth Summit in 1992 in Rio de Janeiro, which resulted in the adoption of *Agenda 21*, agreeing a sustainable model for world development. Although the agreement, Agenda 21 (United Nations Conference on Environment and Development 1992)[405] was short on quantifiable targets, it set the political agenda for the 1990s. A Second Assessment Report (SAR) was published at the United Nations Climate Change conference in 1995, which would introduce targets to stabilise greenhouse gas emissions, creating a framework for the Kyoto Protocol (1997).

The SAR report introduced a sensitivity analysis and scenarios for energy costs and cost projections (IPCC 1995)[406]. The report identified the potential for 10%–30% energy-efficiency gains, at little or no net cost, through technical conservation measures and improved management practices. The report identified the potential for a 25% energy saving in the built environment: "Technical changes might include reduced heat transfers through building structures, more efficient space-conditioning and water supply systems, lighting and appliances" (IPCC 1995)[407].

The IPCC SAR technical paper identified the role of retrofit in delivering building energy conservation savings: "Numerous studies have indicated that 10%–30% energy-efficiency gains above present levels are feasible at little or no net cost in many parts of the world, through technical conservation measures" (IPCC 1995)[408]. The report referred directly to a paper by Dr Witta Ebel (manager of the Passive House Institute in Austria), with regard to the potential for cost-effective energy reduction of 40% in residential buildings in Germany. At the same time, it questioned the potential for cost-effective energy retrofits in the US, citing poor air-tightness and conductive heat loss through windows as being primary sources of energy consumption. This level of insight, in 1995, is built upon precedent low-energy building knowledge. This identifies the clear impact of emergent low-energy building research on the international legislative context. These international agreements would be adopted into regional (EU) Directives and subsequently transposed into national building codes.

The subsequent Kyoto Protocol (1997) and Convention on Climate Change (1998) issued less prescriptive solutions than the SAR report; however, it did identify the role of construction energy in Annex A, as a target category for emission reduction (UN 1998)[409]. The Kyoto Protocol (1997) came into force in 2005.

Following the signing of the Kyoto Protocol (1997), the EU adopted its first Directive on Energy in Buildings (EPB 2002). It claimed that buildings accounted for more than 40% of final energy consumption in the EU (The European Parliament 2002)[410]. It created a clear aspirational roadmap for a cross-national policy to deliver low-energy performance in new and existing buildings. It called for the creation of energy performance certificates for buildings (piloted at *Energy World* in 1985) based on a CO^2 emission indicator, but no set methodology for calculation was set out. In paragraphs 13-15 of EPB 2002, and Article 6, the Directive refers to levels of retrofit, payback periods, energy certification and a base level for retrofit building compliance at a threshold of 1000m^2, effectively confining the regulations to large commercial buildings and excluding most residential applications in Ireland (Slater 2014)[411]. Graph 4.2 illustrates how this threshold would eliminate a very large percentage of Irish commercial buildings.



Graph 4.2 Survey of Irish Commercial buildings by area (Slater 2014)

4.9 Irish legislative response (1997 - 2010)

In 1997, moderate improvements (15%) were made to U-Values in Irish building regulations (Technical Guidance Document Part L 1997).

Proprietary details were introduced for domestic thermal bridging compliance, and air infiltration was referenced as an unquantifiable aspiration. Following the EU Energy Performance Directive (EPD 2002)[412], Irish building regulations further revised elemental performance standards by 10% (Table 4.14), widening the definition and application of air-tightness and thermal transmittance by conductive bridging. However, there was still no requirement for an air-tightness test. It did address fabric heat loss, through pipe and cylinder distribution losses, space heating and water controls. It also provided for a rudimentary calculation for solar heat, appliance, cooking and metabolic gains. These building regulations were intended to cover new buildings and retrofit; however, retrofit elemental standards remain unchanged and potentially unenforceable. "The national regulations do not state minimum packages of measures that should be undertaken during any (or major) renovation works" (AECOM 2015).[413] The 2002 standards for building retrofit have not been revised up to 2016. However, the Department are preparing draft revised Regulations (Part L 2017) for public consultation in 2016.

Irish Building regulations Progression of Energy conservation in Buildings (Dwellings)Average Elemental U-Value in W/m^{2}K								
W/m^{2}K	**1976**		**1991**	**1997**	**2002**	**2005**	**2007**	**2011**
Roofs (flat)	0.4		0.4	0.35	0.25	0.25	0.22	0.2
Walls	0.6		0.6	0.55	0.37	0.25	0.27	0.21
Ground Floors	0.6		0.6	0.45	0.37	0.25	0.25	0.21
Av Elemental Improvement			0%	15%	10%	22%	1%	19%

Table 4.14 Irish Regulations, U-Value evolution

Sustainable Energy Ireland (an NGO) was given an official role in driving Ireland towards the targets of the EPD 2002, when it became the Sustainable Energy Authority of Ireland, a part of the Department of Energy and Natural Resources, under the Sustainable Energy Act (2002). They had a wide remit, one of which was energy in building. However, the primary policyholder of the Building Regulations, the Department of Environment, would remain separate from the SEAI and the Department of Energy, creating a demarcation, or boundary, issue between government departments.

Legislative actions from 2002 to 2008 by EU member states (MS) saw them adopt the environmental targets set out in EPB 2002 into national building regulations, despite the exogenous impact of rising oil prices. This, perhaps, indicates the maturity of the Environmental Movement, that such exogenous energy events did not sway MS political policy. The advent of the EU Energy in Buildings Directive 2002 saw the gradual improvement in Irish energy conservation regulations, through 2005 and 2007, with Building Energy Ratings (BER) being introduced in 2008, with specific targets (less onerous) for commercial applications, quantitative air-tightness targets and the requirement for onsite renewable technologies. The recast of the EPBD in 2010 saw an aggressive roadmap towards Nearly Zero Energy Building (NZEB) performance public buildings in Ireland by 2020. The EU had committed itself to a 20% reduction on 1990 CO^2 levels by 2020 and an 80% reduction by 2050, expanded upon in the next chapter.

4.10 Conclusion

Although a number of seminal writers created an environmental dialogue in the 1960s and early 1970s, Irish government policy would be mainly moved by exogenous events such as the oil crises of 1973 and 1979, Cold War politics, the Stardust fire and Chernobyl. Governments, like the UK and US, focused policy towards energy independence rather than energy conservation. Public attitudes towards mandatory home energy performance were impacted by the UK's policy on energy independence, resulting in government energy conservation actions becoming entirely voluntary. Regulations regarding envelope insulation slowly improved. Early exemplars of low- and zero-energy buildings established the principles of good low-energy design, establishing an envelope first demand-reduction best practice, but had little effect on government policies until the advent of the SAR report and Kyoto Protocol.

The oil crisis changed both public and political perception of energy consumption and the conservation of energy. The creation of the IEA had little to do with the environment and everything to do with security and economics. The price of oil and energy security in the 1970s exerted a decisive influence over the "control systems" that drove the first international regulations on energy conservation, and not the concurrent conflicting actors of environmentalism. Steinmüller (2008) calls into question the contention that scientists and ecological groups alone could achieve transformative change, pressurising public control systems to form a regulatory response, without supporting user and market demands. Legislative responses attempt to internalise the costs of oil exploration by restricting the developments (e.g. US coal burning restrictions), or requiring the environmental impact of developments (e.g. Shale gas development) to be assessed, or taxing the product to subsidise alternatives or fund research (environmental energy levies).

The changing policies of Nixon, Ford, Carter and Reagan demonstrate the impact of different political priorities on the market development and demand for low-energy buildings. Nixon, and Thatcher's extension of Nixon's *Project Independence,* and the falling price of oil, undermined emerging renewable technologies and market demand for low-energy buildings. Payback periods developed in Twin Rivers (1979,) and Home World (1981) was undermined by the falling oil prices. However, they did establish that passive strategies, such as envelope insulation, were clearly far more cost-effective than active systems. The lifespan of active systems at the Green Building in Dublin, and the lack of an integrated system for feed-in tariffs, demonstrated the technical issues facing the use of active systems. Wind was clearly a failure, with ground source heat pumps and PV being more successful.

The lack of mandatory building energy regulation, up to 1992, also undermined market demands for low-energy buildings. The lack of policy intensity of building regulations for retrofit seriously impacts the potential for the market to contribute significantly towards GHG abatement. The lack of any new regulations in commercial “new build” or “retrofit” since the EPBD 2010 could also be reducing market demand, the opportunity for practice experience and opportunity to contribute to GHG emission abatement.

The early projects in Copenhagen, Aachen, Illinois, Saskatchewan and Twin Rivers established the key principals of Passive House Design. Read together, as a sequential development, they established best practice in low-energy design. They established that super-insulation, thermal bridging, air-tightness and shading are key factors in envelope retrofit for low-energy performance. They also illustrated that heat pumps and PV could be used with thermal mass to meet remaining space heating and electrical loads. Passive House strategies could be used, but in a commercial retrofit context the designer should be aware of the potential for higher internal heat gains. Winter solar gain may also not be such an important factor in space heating, for commercial low-energy retrofit.

The key strategy identified by all the exemplars is that a passive energy demand through envelope insulation is the first step, and then augmenting remaining loads with active systems afterwards.

Section 5 of the research, the *Normative Domain*, develops on the topic of payback periods, introducing cost-effective and cost-optimal building retrofit though legislative action. Domain Stage 5 examines EU guidelines for cost-optimisation and how they are calculated in a UK and Irish context, with implication for future revisions of the Building Regulations. Having established the extent of Irish building stock contracted before mandatory regulations, Domain Stage 5 examines the impact of building lifespan on replacement/retrofit investment decisions, passive house making and the potential role for legislation to improve market demand and moderate market behaviour.

CHAPTER 5

IRISH NZEB LEGISLATIVE POLICY AND THE IMPACT OF COST OPTIMAL CALCULATIONS

Chapter 5 Irish nZEB legislative policy and the impact of cost-optimal calculations.

Foreword

Having examined the exogenous factors that influenced the development of low-energy precedent buildings, we have found that factors other than the environment influenced the development of building standards, with regard to energy conservation. Various market barriers were responsible for the failure of low-energy buildings to gain widespread market adoption. More recently, the Kyoto Protocol (1997) influenced the development of European Directives (2002 and 2010) and Irish regulations for the conservation of energy in buildings. This chapter reports on the Irish context and impact of the European Directives, changes to Irish building regulations, compliance issues, market behaviour, the introduction of energy assessment methodologies, the potential for retrofit in an Irish context, government supports for voluntary retrofits, investment barriers, decision-making, cost-optimality and the potential impacts on future regulations Part L 2017.

5.1 Methodological statement

Following Foqué's *Product Context Process* analysis (PCP), the goal of this research stage is to examine the *Normative Domain* (Graph 5.1), mapping the socio-political framework around which buildings are created, the regulations, incentives and laws.

Domain Stage 5 reviews the introduction of normative standards in Ireland from 1992, the impact of the Kyoto Protocol, the introduction of European directives and their transposition in Ireland. This stage involves a critical review of legislative implements and published papers, which frames a dialogue around the topic and its impact on architectural practice. Surveys support contentions of praxis compliance issues. Published cost-optimal nZEB calculations in the UK and Ireland are compared to EU guidelines for compliance, consistency and recommendations, with findings on the potential impact on national emission abatement targets. This stage is entirely based on the review of secondary sources.

The chapter maps some key legislative changes that arise from the Energy Performance Directive 2002 (EPD 2002), to the adoption of *Building Energy Rating* and *Energy Performance Certificates,* the adoption and definition of nZEB in an Irish context, through the transposition of the EU Directives into National laws, reviewing reports, guidance and regulations. The study elicits a growing story of non-compliance, both from industry articles and research studies. Secondary publications were examined along with contemporary reports that support the contention that there was a growing level of non-compliance with building energy regulation in Ireland and the UK (2005-2011). Important contributions from some key authors frame the context of non-compliance: Attia (2009) highlights a low level of building performance simulation usage by architects, Pan and Garmston (2012) attribute compliance difficulties to lack of practice knowledge, with Cox highlighting poor awareness of thermal bridging as a key issue in non-compliance.

The stage introduces a survey of 150 design practitioners (Appendix 5.1) to "estimate with reasonable precision" (Dillman 2011)[414] the adoption of simulation software by architects, compared to engineers, and establishes practice readiness for nZEB. Nesbary (2000)[415] argued that surveys could be used to establish a "representative sample data from a larger population and using the sample to infer attributes of the population". The survey is used to support Attia's contention that engineers more frequently used BPS tools than architects. Note this chapter will refer to nZEB in its regulatory context, rather than NZEB in the context of an overall Net energy balance.

5.2 Introduction

Domain Stage 4 illustrated that political intervention had either promoted energy conservation in buildings, or undermined it. The capital investment/operational cost analysis of low-energy strategies for buildings can be undermined by the volatile swings in the international cost of oil, especially where there is no mandatory level of performance to provide confidence to investors.

Domain Stage 5 addresses how existing design practice can be regulatory compliance-focused rather than building performance-focused for a number of reasons. Indeed, the potential for architects to achieve a measured nZEB performance and possible shortcomings in the training, practice or experience will be addressed. The heterogeneous skill-sets of design teams, the interdependence of design team decision-making and the technical capacity of design teams to achieve a measured nZEB in a mandated Irish regulatory context will be explored. The precedent projects from the early 1970s demonstrate the multivariate skill-sets required to achieve nZEB performance; the subdivided nature of the disciplinary boundaries can potentially contribute to communication and coordination problems, resulting in performance issues. The impact of a traditional praxis over-reliance on accredited standard details in regulations, backstop values, elemental standards, overall heat loss methods and voluntary generic guidance will be explored in the context of the field's ability to respond to future mandatory nZEB regulations.

We look at performance gaps, both systematic and technical, and their impact on the post-occupancy performance of a low-energy building. The *Normative Stage* explores market barriers to the adoption of nZEB retrofit strategies in an Irish context. The artificial division of building energy consumption between fixed and process (plug) loads are examined, together with consequent impacts on the potential for Green House Gas (GHG) abatement.

The transitory period between Energy Performance Directive (EPD 2002) and Energy Performance in Buildings Directive (EPBD 2010) was mapped to demonstrate how the changes in energy in building regulations for new build, the introduction of energy assessment methods, market activation schemes and improved elemental component targets impacted low-energy retrofit adoption.

Whilst Irish Building Regulations for new build have become performance oriented, most of the key envelope compliance targets are still elemental, making compliance accessible to the builder and design team. Unlike the Passive House methodology, elemental values do not add up to an overall building energy performance target. Since the introduction of the EPD 2002, basic elemental targets for retrofit remain unchanged and are very similar to 1976 draft-building regulations for new build. Cost-optimal nZEB guidance has been adopted in an Irish context and the results will inform the revision of retrofit targets in Technical Guidance Document (TGD) Part L 2017. This domain stage reports on the conclusions and recommendations of this cost-optimal report and contrasts the methodology used with UK calculations for cost-optimal. The *Normative* analysis will conclude with a discussion on how these proposed standards may impact design methodologies, the potential for nZEB market adoption and GHG emission abatement.

The proposed Irish cost-optimal compliance-based model was assessed and compared to UK cost-optimal calculations. The application of EU guidelines for cost-optimal calculations was scrutinised for national compliance, interpretation and deviations. Finally, conclusions and findings are presented, to inform low-energy retrofit practice, cost-optimal strategies and how these may impact design praxis through the revision of Part L, with implications for GHG abatement. The following *Functional/Process Domain* stage examines precedent retrofits as part of a process analysis and Foqué's reflective practice, establishing market behaviours, demonstrating the extent of cost analysis and the impact of regulations on design solutions.

5.3 The impact of Energy Performance Directive on Irish legislation for the built environment.

Irish Building Energy Regulations were first introduced in 1992 and revised as TGD Part L in 1997. Following the signing of the Kyoto Protocol (United Nations 1997)[416], Part L regulations were subsequently revised in 2002 (Environ 2002)[417] with the inclusion of building retrofit standards for the first time. The mandatory elemental standards (Environ 2002)[418] were similar or the same as the Draft Building Regulations 1976 (Table 5.1). The EU Energy Performance of Buildings Directive (Europa 2002)[419] was introduced in 2002, in response to the agreed targets for GHG emission abatement in the Kyoto Protocol (1997). All subsequent revisions of the Part L, for buildings other than dwellings, have omitted improvements in retrofit standards, highlighting a low-intensity regulation environment for retrofit.

Irish Building Regulations Progression of Energy Conservation in Buildings **Retrofit** Average Elemental U-Value in W/m^{2}K			
W/m^{2}K	**1976**	**2002**	**2008**
Roofs (flat)	0.4	0.35	0.35
Walls	0.6	0.6	0.6
Ground Floors	0.6	0.6	0.6

Table 5.1: Evolution of Retrofit Elemental Standards in Irish Regulations (Ó Riain 2016)[420].

The EPD Directive 2002[421] set out a roadmap for improving national built environment regulations, primarily for new building stock, targeting a reduction in Irish "emissions by 13% on 1990 levels by 2020" (Environ 2010). In paragraphs 13 to 15 it refers to major renovations, and in Article 6 it encourages member states to set minimum energy performance standards for full or partially renovated buildings over 1000m^2 or for upgraded systems. Very gradual improvements were made in revisions of Technical Guidance Document Part L Conservation of Fuel and Energy, implemented at various stages in 2005, 2008 and 2011. “Since 2008 separate volumes of TGD L have been published in respect of *Dwellings* and *Buildings other than Dwellings*” (Environ 2010)[422]. The 2005 revision targeted a 40% improvement to “energy efficiency and carbon dioxide emissions by 2007”, the 2007 revision targeted a further 20% improvement by 2010 and the 2011 revision targeted carbon neutral dwellings by 2013. “A typical dwelling performance level under Part L of the Building Regulations 2011 is 59 kWh/m^2/yr” (Schimschar, Bosquet and Surmeli 2013)[423]. By 2011, this meant that all new housing had to comply with a building energy rating of A3 at a minimum >50 <75 kWh/m^2yr. The balance of energy consumed could be met with site renewable energy (solar heating or biomass for dwellings). From the 2007 regulations onwards (for dwellings and buildings other than dwellings), mandatory air-tightness, renewable energy components, minimum standards on heating systems with controls and energy efficient light fittings are required for the first time (Thornton 2008)[424].

In 2006, the European Commission proposed to adopt a “binding requirement that all new buildings needing to be heated and/or cooled be constructed to passive house or equivalent non-residential standards from 2011 onwards” (European Commission 2012). Subsequently, Fraunhofer (2009)[425] would develop a proposed EU standard (New 4) based on Passive House standards. ECOFYS (2010) would identify this standard as the ‘high policy intensity scenario’ required, to enable the EU meet GHG abatement targets (Wesselink, B. et al., 2010)[426].

These reports informed the recast of the Energy Performance in Buildings Directive (2010) and the introduction if ‘nearly zero energy buildings’ for new and refurbished buildings. “According to the Directive, a **zero energy building** has a very high energy performance (is highly efficient) and a very significant share of renewable energy for the remaining energy requirement of the building.” The EPBD 2010 would set targets for achieving nearly zero (rather than Net Zero) energy performance "in in so far as this is technically, functionally and economically feasible" (Wesselink, B. et al., 2010)[427]. The EU would later develop Cost optimal nealy zero energy performance, which sought to identify the economically feasible performance level.

A 'nearly Zero energy building' (nZEB) is a deep retrofit, which has achieved a very low level of remaining energy demand by using energy consevraiton measures. A 'Net Zero-Energy Building' (NZEB) has met the balance of energy demand with renewable energy (usually produced on site where there is a lack of grid connection) measured over a calendar year. Ireland does not have a feed in tariff and companies cannot draw down exclusively renewable energy from the grid.

In 2008, a separate Part L was published for buildings other than dwellings, "Part L (Conservation of Fuel and Energy) of the Building Regulations also sets out the statutory minimum energy performance standards for existing buildings undergoing extension, material alteration or conversion from a building previously used for different purposes" (Schimschar, Bosquet and Surmeli 2013). Compliance with Part L 2008 is not mandatory, but only required "as far as practically possible…. the adherence to guidance, including codes, standards or technical specifications intended for application to new work may be unduly restrictive or impracticable" (Environ 2008) [428].

5.3.1 Energy performance measurement and assessment models

The *Building Energy Ratings (BER)* are currently based on *Simplified Building Energy Model* (SBEM) software to calculate the energy efficiency of buildings and the $C0^2$ emissions of buildings (CIBSE 2006)[429]. The Dwelling Energy Assessment Procedure (DEAP)[430], based on the *Simplified Building Energy Model* (SBEM)[431], was required to demonstrate compliance with Part L for all new buildings in 2005 (DoELHG 2005)[432], and BER certificates were made mandatory from 2006[433] for new and existing buildings.

The introduction of DEAP (and later NEAP[4]) as a mandatory assessment model for calculating total energy consumption of a building for compliance to TGD Part L 2005, replaced the elemental and overall heat loss methods (OHL) used since the 1997 regulations (Daly 2006)[434]. Daly noted that OHL has been the preferred compliance calculation method of industry, as it allows significant elemental U-Value relaxations from the "elemental" maximums. Daly's inference may point to a normal building practice focus on the minimum level of compliance rather than be performance oriented.

Design compliance no longer depends on the elemental performance, but on the dimensions and design of the overall building performance, when compared to a 2005 reference building. To identify if a design is compliant, all the details have to be entered into DEAP or NEAP software, resulting in an energy performance coefficient (EPC). "To comply with the 60% energy reduction (dwelling) in the new TGD L (2011), your maximum permitted energy performance coefficient (MPEPC) must be a figure of 0.4 or less, compared to a reference house EPC of 1" (Colley 2011)[435].

Since the introduction of Technical Guidance Documents (TGDs) in 1992, the publications have included U-Value tables with backstop values and Acceptable Construction Details (ACDs). These have made the interpretation of the guidance simpler and more accessible. The Royal Institute of Architects in Ireland (RIAI) argues that following Part L 2011 "backstop values will probably result in non-compliant buildings" (RIAI 2010)[436]. The reasons for this are that the design of the various components is now more complex and inter-related. "Currently if you only want to calculate a Y-value (Psi-value for thermal bridging) of 0.08 (as

4 Non-domestic Energy Assessment Procedure (NEAP) and iSBEM software (Simplified Building Energy Model), are used both to demonstrate compliance with the building regulations for buildings other than dwellings and for post-occupancy display energy certification. iSBEM was originally based on the Dutch methodology NEN 2916:1998 (Energy Performance of Non-Residential Buildings) modified for EPBD compliance and is a steady state (not dynamic) forward modelling approach.(Wang, Yan and Xiao 2012.)1. The software, which is not a design tool, captures a "standard set of data for different activity areas and call[s] on common databases of construction and service elements...for consistent and reliable evaluations of energy use in non-domestic buildings for Building Regulations Compliance and for Building Energy Performance Certification purposes"(BRE 2015)4. NEAP, which had been developed after its domestic counterpart (DEAP) had been applied to Part L 2005, was originally based on SAP and EN13790 and is "based upon the UK's national calculation procedure—SAP 2005" (Daly 2006)4.

opposed to using the default value) you may have to abandon the ACD details, for certain dwelling geometries and construction types. If you want to go further, as the department felt obliged to do, to prove compliance [in the regulatory impact assessment document], you may not be able to use the ACDs at all" (Colley 2011)[437]. The standard practices of architects, in using elemental backstop values and acceptable construction details have, in the recent past, allowed them to design compliant buildings without needing to understand the complexities or building physics or use complex software. However, since the introduction of increasingly onerous EPCs and standard energy performance software to assess designs, architectural practice has had to change. The question is: How successfully has it made that transition?

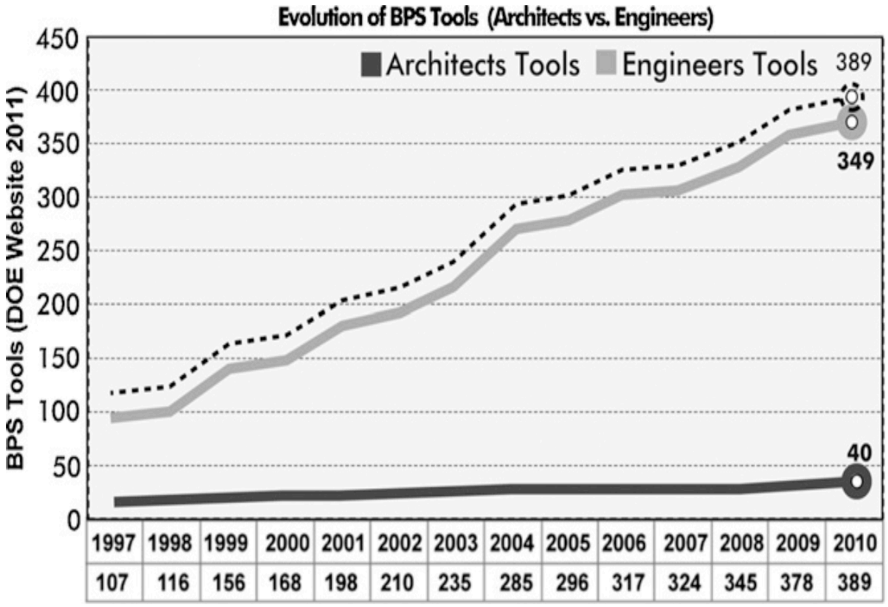
5.3.2 Compliance issues

Architectural practice may be regulation compliance-centric when developing new designs, in the absence of other performance metrics or targets: "A survey on UK architectural design practices to assess the impact of current energy conservation policies and legislation stated that 80% of the surveyed sample indicated that Part L (compared with government white papers and good practice guides) had the foremost impact on the design of low-energy buildings" (Hamza and Greenwood 2009)[438]. The steady improvement in Part L regulations since 2002, changing compliance protocols and the confluence of the recession may have contributed to the dramatic drop in building energy compliance; non-compliance to energy in building regulation rose from 21% in 2005 to 67.5% in 2012 (Antonelli et al. 2012)[439]. Hull, Ó Gallachóir and Walker (2009)[440] established that there was a culture of non-compliance with historic building regulations in Ireland. In a similar UK study, Trinick et al. (2009) discovered that 20% of SAP assessment for new buildings was non-compliant with Part L (Trinick et al. 2009)[441]. Fisher identified the weak state of enforcement as a potential reason for such a low level of compliance (Fischer 2009)[442]. Thornton highlighted that the low level (12-15%) of enforcement inspections could be contributing to a culture of non-compliance (Thornton 2008)[443]. The NESC reported that "Ireland's record of poor compliance with, and enforcement of, building regulations" (National Economic and Social Council 2012)[444] is impacting the potential of retrofit to play its part in meeting GHG emission abatement.

Pan and Garmston (2012) warned that the increasingly stringent building regulations were contributing to an increasing incidence of "non-compliance in practice", identifying "a lack of knowledge" as a potential factor.[445] Pan et al. (2012) recommend a greater level of training and education for the multiplicity of stakeholders. Supporting this contention, Cox (2006) surveyed 59 building control officers in the UK (who have very similar targets in Part L) and found that "compliance (with Part L) was poor compared to other elements of the regulations…Thermal bridging was shown as the worst area for non-compliance", with U-Values and compliance with insulation standards also being poor. Cox identified "onsite cost-cutting, ignorance and a lack of knowledge" amongst the design team and the contractors as key factors in compliance failure: "the construction industry is resistant to change and there is perceived to be an increasing gap between skill levels and the demands of regulations. It was perceived that the building regulations were too complex for many parts of industry" (Cox 2006)[446].

The changing nature of Part L regulations has placed a greater emphasis on building energy performance. The historical dependence on ACDs and backstop values to achieve Part L compliance by architects is no longer sufficient to meet building standards. New tools, like Building Performance Software (BPS), are needed to validate design decisions. The use of specialist software, such as DEAP for generating EPCs, Therm for assessing thermal bridging, WuFi for analysing condensation risk, and IES for assessing heat gain and day lighting may be beyond many architects.

Attia reports, "from the perspective of many architects, most BPS (Building Performance Software) tools are judged as too complex and cumbersome" (Attia et al. 2009)[447]. "Architects suffer from BPS tool barriers during this decisive phase, that is more focused on addressing the building geometry and envelope. In fact, architects are not on board concerning the use of BPS tools for NZEB design" (Attia et al. 2009)[448](Table 5.1). Indeed, Attia's study found that architects found it hard to use simulation modelling in design practices. However, as early as 1979, Wayne Schick and his team for the Lo-Cal House demonstrated the use of computer software to predict building energy performance (Shick 1979)[449].



Graph 5.1: Evolution of BPS Tools in the last 10 years. (Attia, S. et al., 2012)[450]

5.4 Survey of the use of simulation software in Ireland

Both the introduction of software-based assessment methods (2005) for regulatory compliance and the impending revision of the Part L in 2017, offered the opportunity to the researcher to assess the use of simulation software in Irish design practices. The research discovered an indicatively low level of simulation and scenario analysis in practice. New accredited industry roles had developed - Building Energy Assessors - outside the realm of the design team. Questions arose: Were completed designs run through the (iSBEM) software by external contractors from the design team, and were recommendations for changes coming back? If so, did this result in a disconnection, leading to a knowledge gap in architectural practice, which might impact praxis ability to achieve compliance with more rigorous future nZEB legislation? A survey was carried out amongst 150 industry professionals, across a range of design team disciplines in April 2015.

5.4.1 Survey structure

"Survey research is the process of collecting representative sample data from a larger population and using the sample to infer attributes of the population" (Nesbary 2000). The purpose of a survey of design team participants is to "estimate with reasonable precision" (Dillman 2011)[451] the adoption of simulation software by architects compared to engineers and to establish practice readiness for nZEB.

As part of this body of research, a survey of practitioners was carried out across the range of the disciplines in a typical project team. Survey questions were limited to 10 to increase completion rates, and questions sought to establish the building professionals' familiarity with nZEB, the use of simulation in their practice, the frequency of its use, the barriers to its more widespread adoption and knowledge of cost-optimality. Questions were simple and short to identify any disciplinary variations in attitude or practice. Complex questions were avoided, as comparing results would be less practical.

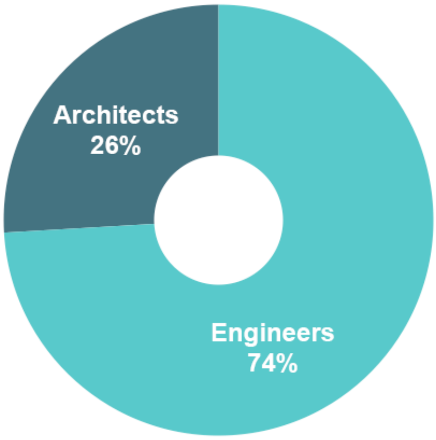
Ten questions were asked on one page, with multiple-choice answers. There were 150 respondents to the online survey carried out over a 20-day period in July 2015, with 100% of respondents answering all or most of the questionnaire. Responses were sought through the architecture, engineering and design representative bodies in Ireland. A wide, online canvass of the predominantly Irish building professionals was carried out, using online tools *Survey Monkey*, *LinkedIn*, *Facebook*, other social media and email, resulting in a relatively good sample selection. A broad spread of building professionals responded, with architects (44%), interior architects (17%), architectural technologists (12%) and engineers (19%)

representing 92% of all respondents. The other 8% were made up of project managers, facilities team and quantity surveyors.

5.4.2 Survey results

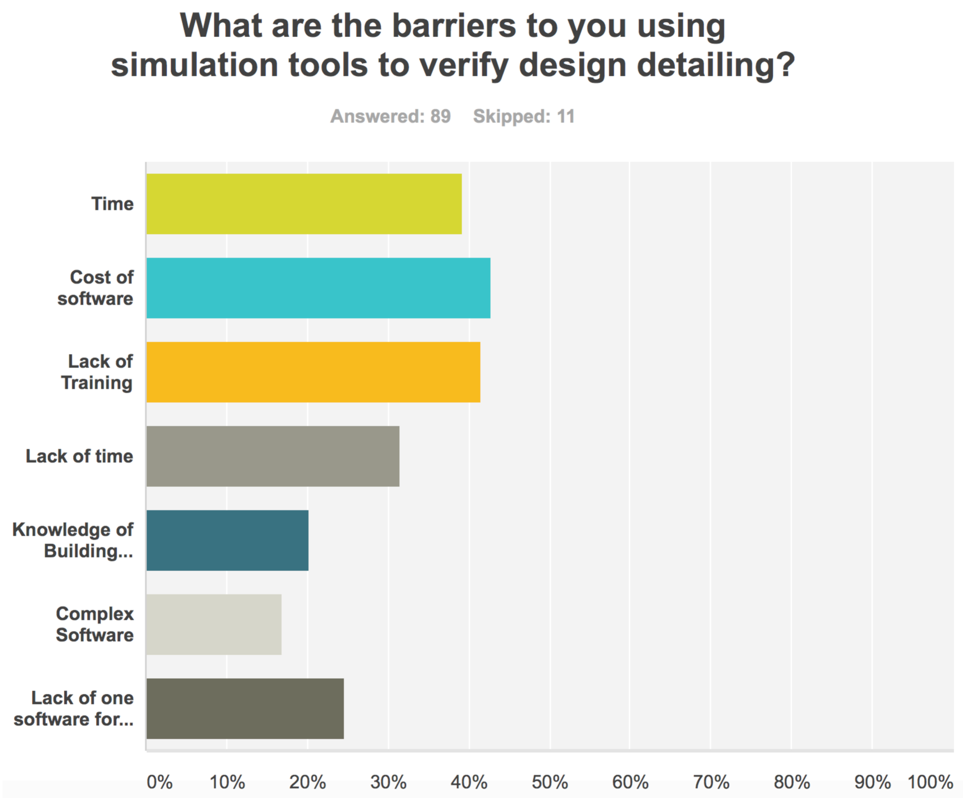
[See appendix 5.1 for full survey details and responses]

The results and findings from the survey are summarised here as they apply to the use of BPS tools, barriers to their adoption and the ability of architectural practices to respond to nZEB.



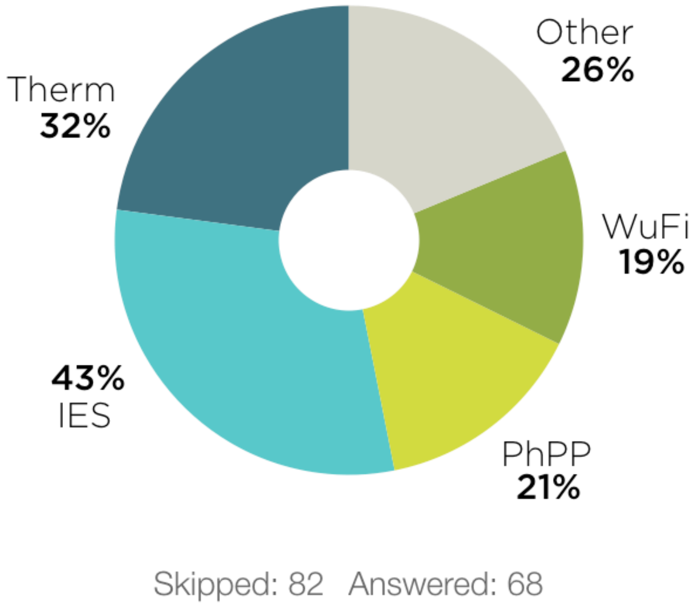
Graph 5.2 Use of simulation tools by architects vs. engineers in Ireland

Fifty percent of respondents to the survey rated their familiarity with nZEB building energy design as reasonable to good, and 90% believed energy simulation to be an important tool to be used to achieve nZEB design. Only 20% of respondents had built or retrofitted to an nZEB or Passive House standard, with only 33% of all disciplinary practices using simulation tools. However, when we delve into this figure we find that 74% of engineers used simulation, compared to only 26% of architects (Graph 5.2).



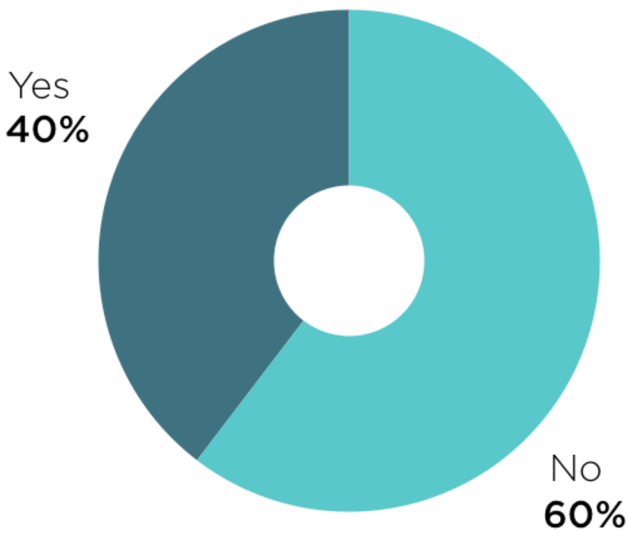
Graph 5.3 Barriers to the use of simulation tools.

Sixty-two percent of respondents cited lack of time, training and the cost of software as the main barriers to more widespread simulation adoption in their practice (Graph 5.3). The results were similar for architects even though Therm is free software. The complexity of software (21%) and the lack of a single software for all needs (25%) was also a cited as barriers to adoption.



Graph 5.4 Simulation tools used in professional building design practice.

Almost no one had heard of cost-optimal nZEB (16%) and 60% of respondents did not feel their practice could achieve nZEB building performance. Worryingly, for the potential adoption of NZEB, only 40% of architects felt competent to deliver a measured nZEB performance (Graph 5.5).



Graph 5.5 Architects belief of their ability to achieve nZEB performance.

5.4.3 Survey Findings

There is clearly a low level of simulation usage in architectural practice in Ireland, when compared to engineering. The results of the use of the Passive House Planning Package (PHPP) (Graph 5.4) would suggest that simulation usage amongst architects is highest amongst those with Passive House training. The very low level of familiarity with cost-optimal calculations would suggest a low use of cost-based scenario analysis in decision-making. The apparent low level of simulation adoption would suggest that Irish architectural praxis is not equipped with the toolsets to respond to the EPBD targets for nZEB performance, either through new build or retrofit, supported by the fact that 60% of architects believe this to be the case. One might infer from the results that the engineer or other compliance specialist may be responsible for ensuring energy performance compliance. Hamedani and Smith (2015) have recently reported "Building energy performance simulation still has a low impact in the building design sector, especially in design decision-making in earlier stages of design" (Hamedani and Smith 2015)[452]. Therefore, as Pan and Garmston (2012) contend, there is a need for a greater level of education and training in design practice: "More consistent energy assessment reporting and checking should be encouraged, and education and training should be provided, to raise awareness of energy efficiency building regulations to enhance knowledge, [and] skills" (Pan and Garmston 2012)[453].

5.5 Design simulation and communication

"Communication that is not clear can result in unsatisfactory design results for the client" (Ayodele 2008)[454]. McElroy (2009)[455], writing on the importance of simulation to the design process, emphasised "communication of design ideas and simulation capabilities between designers from different backgrounds, can lead to confusion" (McElroy 2009). Ding (2008), concluding on environmental assessment methods, also highlights that "there is a requirement for greater communication, interaction and recognition between members of the design team" (Ding 2008). The widening gaps between professionals collaborating on a specific project can produce silo-based decision-making, where certain design decisions are made in an engineering office and, perhaps, not discussed together as a team (Lewis 2004). Design practice "generally proceeds in a linear, non-collaborative sequence, where little constructive collaboration occurs among design disciplines…promoting a lack of communication between disciplines, which undermines ability to integrate sustainability measures." (Lewis 2004)[456].

With the disparity in the use of BPS by architects and engineers (Attia 2009) (Ó Riain 2015), most of the performance-oriented decision-making could be made in the engineer's office. However, decisions made on low-energy buildings are inter-dependant, involving multiple disciplines: "In the case of day lighting, virtually every design discipline is affected, including architecture [building envelope and orientation, lighting design], structural [floor-to-floor heights], mechanical [reduced internal loads, modified skin loads], electrical [lighting design and lighting controls], and interiors [interior colours and reflectances]. In the example of natural ventilation, a total interconnection exists between architecture [building orientation, fenestration] and mechanical engineer [design of HVAC system and controls]" (Lewis 2004)[457].

A performance oriented design process requires each discipline to thoroughly understand each other's role, to allow an adequate and informed evaluation of architectural and engineering decisions on capital and operational cost. The subdivision of roles and the quick iteration cycles expected in a design process, may infer that a breakdown in effective decision-making, or silo-based (single discipline) decision-making, as Lewis (2004) put it, would impact on the ability of the team to effectively evaluate each decision collectively. "The achievement of an integrated design of the building requires, in particular, collaboration in determining the shape, orientation, fabric and systems of buildings. This entails significantly more analysis than was traditionally required, when an elemental approach to energy regulations was sufficient and often the main decision was whether or not air conditioning would be required by the client" (CIBSE 2006)[458].

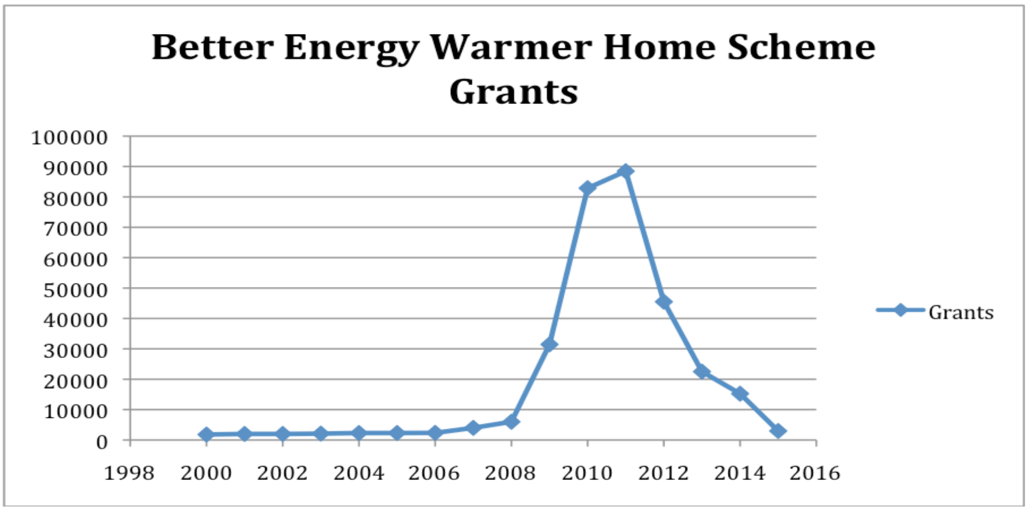
As Ochoa (2008) states, the design process is iterative, moving from the abstract to the specific. "As it advances and more specialists are called in to solve details, earlier decisions, which could have an enormous influence on the building performance, are expensive and harder if not impossible to change" (Ochoa and Capeluto 2008)[459]. Becker (1999) notes "the explicit application of the performance concept during decision-making phases of a given building project, and mainly during project initiation, is generally still minimal" leading to performance target gaps. Ensici et al. (2008) reinforces this: "Decision-making as part of the design process is one of the most important issues that directly influence the success of the product…and individual contributions can vary considerably within a team" (Ensici, Bayazit and Lauche 2008)[460].

Haymaker (2011), commenting on the *Sustainable Building Design Processes* said, "project teams lack socio-technical platforms that allow them to relate and communicate all of this new design information effectively and efficiently" (Haymaker et al. 2011). He continues "project teams fail to communicate important components of design rationale, including the identity of stakeholders, their objectives, and the analyses required for these objectives…we find that underrepresented teams are developing inadequate statements of objectives and analyses, and are relying on potentially invalid precedent knowledge to perform limited and superficial search of poorly defined and communicated design spaces" (Haymaker et al. 2010)[461]. This has an important potential impact when considering performance-oriented design teams.

The lack of use of simulation software by architects creates a situation where validation of design decisions depends on the engineer, and then the quantity surveyor to cost. The paradigm shift in building regulation compliance requirements has not been mirrored by a similar shift in architectural and design praxis. BPS tools, for example, have not been widely adopted by architectural practices in Ireland. The lack of simulation skills and adequate communication structures prevent the development of sound energy efficient schemes at an early stage of the design process. The impact of poor communications within the design team could lead to poor building energy performance, potentially leading to non-compliance with regulations. The iterative nature of architectural projects (Lewis 2004) and simulation modelling (McElroy 2009)[462], therefore, require praxis to move to a more integrated collaborative paradigm in the context of achieving more onerous energy performance targets associated with nZEB retrofit or, indeed, new build.

5.6 Policy Intensity

The Irish government is obliged to meet the targets of the Kyoto Protocol (1997), following the Energy Performance Directive 2002. The statutory implements it uses are building regulations, along with other market activation tools like grants, to stimulate demand, as demonstrated with the loft insulation grants in the late 1970s and early 1980s in the UK and Ireland. Significantly, Ireland has projected that it needs to encourage 100,000 retrofits per year (National Economic and Social Council 2012)[463] to meet its GHG targets in the built environment sector.



Graph 5.6: Better Energy Warmer Homes Scheme grants collated statistics 2000 - 2015 (SEAI 2016)[464].

Grant schemes adopted by the Irish government include the *Greener Homes Scheme*, which was introduced by the SEAI, funding 33,000 installations of renewable heating in homes, from 2006 to 2011(National Economic and Social Council 2012)[465]. The *Accelerated Capital Allowance Scheme* was introduced in 2008 to allow companies to invest in energy efficient equipment. Within building retrofit, the grant is limited to active systems such as lighting, heating, cooling and control. Schemes such as the *Better Energy Workplaces* fund provided grants from 35%-50%, (from €20,000 to €500,000), disbursing €11 million in 2011 to co-finance 85 projects (SEAI 2011)[466]. The *Warmer Homes* schemes focused on fabric retrofits, renewable technologies and heating controls. These were very popular, peaking in 2010-2011 with an average nearing the 100,000 retrofit targets in those years (Graph 5.6), with roof and cavity insulation accounting for 50% of the funded actions. Commercial energy users are failing to realise energy savings because of a lack of information to infom investment decision-making. The National Retrofit Strategy (2014) found that commercial enenergy isers depended on bills for energy consumption and failing to act on energy performance improvements due to a lack of knowledge, the business case for improvements, a "lack of expertise or resources for project design and implementation… consumers don't always have the knowledge and skills required to determine the optimum balance between investment costs and life cycle operating costs. [Furthmore in] the recession and post recssion "credit constrained economy, capital is scarce in many businesses and investment decisions tend to taken over relatively short timeframes of three years or less. The application of onerous payback or rate of return financial assessment hurdles to energy efficiency projects may be a barrier to their implementation (Department of Communications Energy and natural Resources, 2014)[467].

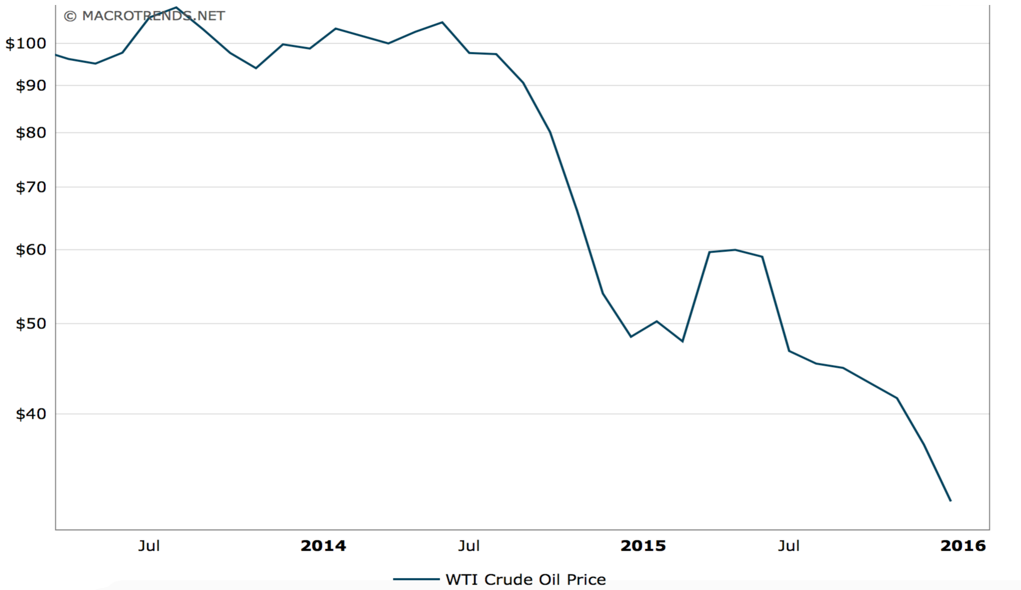
Irish energy suppliers financed retrofits through Energy Service Companies (ESCOs) (Bertoldi, Boza-Kiss and Rezessy 2007)[468], but with "few companies in Ireland that offer ESCO-type services" and with Bord Gáis (one of the main Irish energy suppliers) leaving the ESCO market in

2013 ”following a drastic decline in the number of applications for *SEAI's Better Energy Home* grants for insulation, boilers and solar thermal panels” (Antonelli 2013)[469], sources for financing energy retrofits were falling. The SEAI trialled the Better Energy Finance Scheme with a number of Credit Unions, but initial results indicate a low demand amongst householders for higher loan rates to finance energy retrofits (Donohue 2016). The IEA have highlightted that ESCOs can focus on light retrofit options over deep retrofit, “ In some circumstances, ESCOs may tackle only simple, low-cost actions and avoid more complicated measures or deeper retrofits” (IEA 2015)[470].

Whilst increases in energy prices and the availability of grant incentives from 2008-2011 may have helped move retrofit numbers towards the government targets of 100,000 per year, the Irish economic downturn of 2008-2012 resulted in less credit being available to fund the upfront costs of retrofit (Department of Communications Energy and National Resources 2014)[471]. The collapse in retrofit grants was not ameliorated by a “pay as you save scheme” or better energy financing scheme (Dowd and Browne 2013)[472]. Whilst the government did introduce a VAT relief scheme for house renovations in 2014, this was not linked to energy and could not be used in conjunction with an SEAI grant. The confluence of reduced incentives, a poor level of mandatory regulations, constrained access to finance, a lack of knowledge, information and expertise to inform energy retrofit analysis, biases the market toward short payback energy conservation measures and away from deep retrofit measures associated with deep retorfit. The resultant trend has very worrying implications for Ireland’s potential to meet GHG emission targets, as retrofit levels move towards 10% of their intended annual targets. Although this relates to the domestic home energy market, many of the same issues are analogous of the commercial market.

“The European Union has made good progress on reducing greenhouse gas emissions (GHG) but Ireland is lagging behind most other Member States.” As a result of the recession, there has been a reduction in car traffic, less industrial activity and a collapse in construction activity, resulting in a 9% reduction in GHG emissions, thus allowing Ireland to meet its targets in 2012 (NESC 2012)[473]. Ireland had committed to a 13% reduction in GHG emissions by 2012, but only managed a 4% reduction between 2001 and 2008 (NESC 2012). "Household sector emissions increased by 11.1% from 13 million tonnes in 2003 to 14.5 million tonnes in 2007. From 2007 to 2012, GDP contracted by 6.8% and emissions have fallen by 16.7% since 2007, to 12.1 million tonnes in 2012" (CSO 2014) [474].

As we come out of the economic downturn (where construction activity had collapsed by 73% 2008-2011, Central Statistics Office 2012)[475], our legislative instruments, enforcement, market activation and incentives may not have been sufficient alone to deliver 13% GHG emissions in a normal case scenario. Already there are indications of GHG expansion, with increased economic activity: The EPA reported in mid-2014 "emissions in 2020 will be 5-12 per cent below 2005 levels and will not meet the 20 per cent reduction target" (Environmental Protection Agency 2014)[476]. Dr Eimear Cotter, Senior Manager, EPA said: "We need to translate our national commitment to a low-carbon future into action on the ground if we are to deliver the required emission reductions" (EPA 2014).



Graph 5.7: Crude oil barrel prices 2014-2016 (*Microtrends* 2016).

In light of these developments, significant improvements would be needed to deliver a 20% reduction on 1990 levels of GHG emissions by 2020. For low-energy retrofit to play a role in these abatement targets, significant barriers need to be addressed: lack of financing for deep retrofit, inadequate incentives and insufficient mandatory standards in relation to both the dwelling and non-dwelling sectors. However, in the context of falling oil prices since mid-2014 (Graph 5.7), both the public priority towards energy efficiency and demand for low-energy retrofit may be falling. The International Energy Agency has reported that retrofit investment levels are driven more by building standards than energy prices highlighting the importance of high policy intensity regulations (IEA, 2015.)[477]. In fact building energy retrofit is the highest value and fastest growing energy efficiency sector in Buildings, Industry and Transport (Table 5.2, IEA 2015).

	Total spending	Incremental investment	
	USD billion	USD billion	Change compared with 2014
Buildings	388	118	9%
Envelope	*237*	*56*	
HVAC and controls	*76*	*27*	
Appliances	*34*	*12*	
Lighting	*41*	*22*	
Industry		*39*	4%
Energy-intensive industry		*19*	
Other industry		*20*	
Transport	--	*64*	3%
Light-duty vehicles	*330*	*34*	
Freight vehicles		*2*	
Other transport		*28*	

Note: HVAC = heating, cooling and ventilation.
Sources: Analysis based on Navigant Research, Consortium for Energy Efficiency, IHS Polk, IEA 4E Technology Collaboration Programme.

Table 5.2: Global market for energy efficiency by sector, 2015 Total (IEA 2015)[478].

In 2008, attempting to influence public priority toward energy consumption in vehicles, a previous government administration linked car tax to car emisisons, changing market behaviour overnight toward the purchase of low emission vehicles. There is a potential to consider a similar action linking building energy consumption to property tax, with income ringfenced to finance deep retrofit grants and a zero interest retrofit bank. If this could be augmented with zero rating value added tax for deep retrofit products (like external insulation, triple glazing, and heat pumps), increased intensity nZEB retrofit regulations, and long term PAYE tax relief for deep retrofits, market demand for Deep Retrofit could also be changed. In the context of both the EPBD (2010) and COP21[5] (UNFCCC Conference of the Parties 2015)[479], the Irish Government has committed to making these emission targets; however, their policies to date have resulted in a low diffusion through building retrofit. Although the government published a National Renovation Strategy in 2014 identifying a number of the key barriers to deep retrofit, high level workshop on large scale deep renovation in 2016 have identified that the same issues persist with few policy measures adopted or revised since the 2014 report. Although the report noted the "progressively more stringent building regulation" for dwellings, there was no improvement in commercial building energy regulation up to 2014(Department of Communications Energy and natural Resources, 2014)[480]. Therefore, we will examine in more detail the potential for improved mandatory standards in the forthcoming revision of energy buildings regulations Part L 2017.

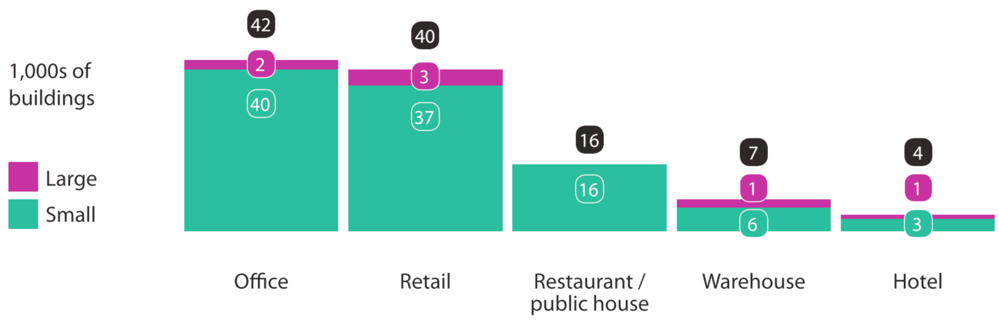
5.7 Revisions to Part L and EPBD guidelines

ECOFYS and Fraunhofer (2010)[481] reported that because of the recent low-intensity EU environmental policy towards energy conservation, a tripling of EU energy conservation policy was required to deliver a 20% emissions savings target, through the period to 2020. Rozite (2006)[482] and Schleich (2008)[483] offered that access to capital and investment priority may be major issues for public, private, large and small organisations' take-up of energy efficient measures. Fraunhofer (2009) had reported that new and existing buildings could deliver 80% GHG emission reductions by "better insulation of the different components of the existing building stock" (Fraunhofer 2009)[484]. Fraunhofer noted that building regulations

5 The international political response to climate change began at the Rio Earth Summit in 1992, where the Rio Convention included the adoption of the UN Framework on Climate Change (UNFCCC). This convention set out a framework for action, aimed at stabilising atmospheric concentrations of greenhouse gases (GHGs) to avoid "dangerous anthropogenic interference with the climate system." The UNFCCC, which entered into force on 21 March 1994, now has a near-universal membership of 195 parties.

mostly referred to new buildings and that a low regulatory environment existed for renovation of older buildings, stock with the greatest energetic conservation potential. In this context, renovation proceeded, for the most part, autonomously from regulations and energetic potential. The report (Fraunhofer 2009)[485] suggests that buildings pass their expected lifespan or renovation cycle before they receive elemental improvements, resulting in EU renovation rates of 1.2% of building stock per annum in north west Europe, with only 40-60% of these buildings being renovated energetically. Combined with the fact that 60% of the EU27 building stock predates 1975 (EU 2007)[486], there was an obvious potential in a *High Policy Intensity* scenario, to radically reduce $C0^2$ emissions, through aggressive retrofit regulations.

In a recent report on the commercial building stock in Ireland, the SEAI highlighted that more than 50% of the surveyed stock dating from 1919-1992 (pre-regulation) were predominantly cavity wall construction, with a high-energy demand profile and a low insulation profile. Of these, the vast majority (Graph 5.8, green colour) of buildings are less than $1000m^2$.



Graph 5.8: Model of the Irish commercial buildings stock by activity type and size (Slater 2014)[487].

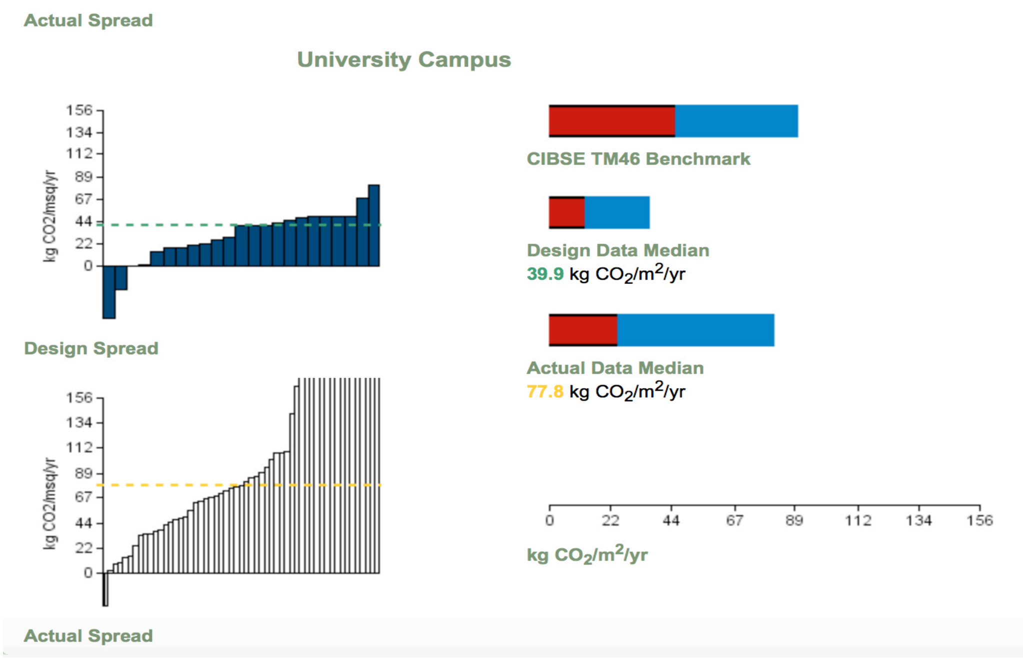
The Energy Performance in Building Directive[488] was introduced in May 2010 to reduce energy consumption in the EU by 20% and analogously, CO^2 emissions by 2020. It included “major renovations” (European Commission 2010) to commercial and residential buildings and sought to target nZEB (Nearly Zero Energy Building) performance buildings. Article 7 of the Directive refers to minimum energy performance standards for the cost-optimal refurbishment of any building over 1000m^2, "in so far as this is technically, functionally and economically feasible" (European Commission 2010)[489]; however, this would later be amended to 25% of the envelope. Whilst Article 9 is clear in citing the requirement for nZEB performance for all new publically owned and occupied buildings by December 31st 2018, the inferred performance of retrofits or major renovations would seem more obscure. The Directive uses the numerical indicator kWh/m^{2}yr rather than KgCO^2/m^2/yr, changing the emphasis from emissions to energy, driving the dialogue towards operational cost and capital return on investment, and seeking to address the bounded rationality of investors or operators (Schleich et al. 2008)[490]. Schleich argues that investors are more likely to respond to indicators to which they can give a value. The limitation of the definition to buildings over 1000m^2 means that the Directive will not relate to 85% of the non-dwelling building stock in Ireland under 1000m^2(Graph 5.8).

5.8 Energy consumption Boundary issues

In drafting the Directive 2010/31/EU (building energy), and Directive (2010/30/EU (energy in products), the EU artificially separated fixed energy consumption in buildings from non-fixed energy consumption in buildings. The EPBD Directive for Energy in Buildings (31/10) was limited to fixed loads, heating, cooling, ventilation, hot water and lighting, excluding plug loads or general unfixed services associated with Directive 30/10. A trickledown effect resulted in member states' building energy codes: they became fixed-lighting and equipment centric, by omitting plug loads, which has a consequent impact on design team predictive modelling. Menezes (2012) would later highlight this unfortunate legislative limitation as giving rise to perceived energy performance gaps, associated with plug and other unregulated loads (Menezes 2012)[491]. Display Energy Certificates (DECs) are an indicator of post-occupancy energy performance in commercial buildings, which, for the first time in the design process, include unfixed (plug) loads.

This is important because there may be four main impacts of higher DEC ratings for nZEB building retrofits. Firstly, building operators may be surprised at the apparent poor level of performance, compared to design stage predictions, leading to a "credibility gap" (Leaman and Bordass 2014)[492]. Secondly, the higher level of electrical consumption may have an impact on the choice of renewable technologies in an NZEB post-occupancy demand profile. Thirdly, payback methodologies may have been predicated on design stage energy consumption. Lastly, the potential for GHG reduction can be lower because the design stage is omitting a key energy demand, due to artificial boundary issues in NZEB retrofits.

To quantify this, plug loads, or plug loads, typically account for 10% to 15% of a commercial building's total energy consumption (Dixon-Smith et al. 2011)[493] and can account for upwards of 50% of low-energy buildings' total energy consumption (Graffy 2008)[494]. Carbon Buzz[495] (a voluntary survey of energy consumption in buildings) clearly demonstrates that in education buildings post-occupancy energy performance is 49% higher than the design stage prediction (Graph 5.9).



Graph 5.9 Education buildings energy performance gap (CarbonBuzz.org 2015)[496].

The Directives at EU - and not member state - level bound the focus of building regulations. Whilst this created a consistent treatment, it also enforced artificial boundaries in actual building consumption. MS regulations must comply with EU directives, and thus, design teams comply with building regulations, omitting an important part of the building energy demand matrix. This will compound real and perceived design stage/post-occupancy performances gaps and continue to give a false design stage picture of the demand mix. A higher energy demand (associated with higher electrical demand- plug loads) might favour investment in PV as a renewable, making the payback period shorter. Performance gaps will do little to inspire consumer confidence, and thus, contribute to a credibility gap (De Wilde 2014)[497].

5.9 Cost-optimal nZEB

Following the adoption of the Energy Performance in Buildings Directive (Directive 2010/31/EU), the EU published cost-optimal guidelines and regulations in 2012, to be adopted by EU member states by 2016 (Delegated Regulation EU244/2012). This section of the chapter addresses its interpretation by Irish authorities. The result of Irish cost-optimal calculations recommends an active first basis for Irish legislation, explicitly eliminating fabric retrofit for cost-optimal nZEB (AECOM 2013 and AECOM 2015). However, the Irish calculations fail to address issues of net present value, building lifespan and internal environmental conditions within their scenario analysis. This is important because of the potential for cost-optimal recommendations to inform the revision of the existing building regulations (Technical Guidance Document, Part L 2008) in 2017, and subsequent market adoption of nZEB retrofit practices. Fabric insulation has been key to energy conservation in NZEB strategies since the earliest exemplar in Copenhagen, in 1974. The omission of fabric super-insulation from Irish *Cost-optimal nZEB* would represent a significant departure from established best practice. The absence of fabric retrofit would essentially limit building lifespan, at the end of their existing functional lifespan, particularly for 1960s and 1970s buildings. Calculations may underestimate the impact of fabric-related energy losses on end-of-calculation macro-economic costs, resulting in increased space heating demands, less consistent thermal comfort and potentially poor indoor air quality.

Various legislative implements arising from the recast of the Energy Performance in Buildings Directive 2010 (Directive 2010/31/EU) have been examined, both the Irish interpretation of the cost-optimal methodology for nZEB (AECOM 2013[498] and 2015[499]) and the UK reports on cost-optimal calculations (Department for Communities and Local Government 2013)[500]. Gap analysis highlights differences in the application of EU guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 to the Irish cost-optimal calculations (AECOM 2013 and 2015). Additional interviews and communications with the Irish *Cost-Optimal* authors, the Department of Environment, and other stakeholders were carried out by the researcher (appendix 5.2), to clarify their interpretation and application of Directive (EU 244/2012) guidelines. In 2013 the EU requested additional calculations from the Irish government and these were submitted in February 2015.

The results and recommendations of the Irish and UK cost-optimal reports differ significantly. Existing UK retrofit regulations are more stringent and enforceable than Irish regulations. Existing Irish regulations are very close to 1976 draft standards (Table 5.1), yet Irish cost-optimal nZEB calculations do not recommend elemental improvements and the UK cost-optimal nZEB calculations recommend standards comparable with existing Irish new build regulations (Table 5.5). A critical analysis of why these differences arise was carried out. Both the Irish and UK calculation reports were examined, testing their compliance with EU Cost-Optimal Regulations, comparing methodologies and reference building applications.

Supporting literature on cost-optimality and *Passive House* design principles inform the analysis and critique in this study. A comparison of reference buildings, in both Irish and UK cost-optimal reports, has been carried out, in a broadly similar building code and climate condition context, on both islands. Differences in boundary sets are discussed, with specific regard to reference buildings, occupancy profiles and cost-optimal calculation recommendations. This analysis excludes comparisons of new build or residential sectors and is specifically interested in outcomes for naturally ventilated commercial and public buildings.

Delegated Regulation EU 244/2012 provided a template for scenario analysis from which governments could develop cost-optimal packages for retrofit, based on a 20-year calculation lifespan for non-public buildings and a 30-year lifespan for public buildings, using a number of specific macro-economic inputs and exclusions. EU 244/12 provided "a comparative methodology framework for calculating cost-optimal levels of minimum energy performance for buildings and building elements… Where differences in air quality and comfort are made transparent" (European Parliament 2012:8)[501]. The delegated regulation specifically states that a cost-optimal calculation or amortisation period cannot extend beyond the current lifespan of the existing building, and if the "reference building's remaining lifecycle is shorter than the calculation period, the maximum remaining lifetime could, in this case, become the calculation period" (EU 244/2012).

The Irish government first reported the results of these calculations in March 2013 and the EU requested the provision of further calculations for retrofit, which was submitted in February 2015. If accepted by the EU, the Irish cost-optimal calculations will become the basis for a revision of the TGD Part L (2017) for buildings other than dwellings. As demonstrated by the level of non-compliance with the minimum levels of existing Part L Building Regulations 2008, Part L standards often become the baseline target for value-engineering decisions on cost in new build and retrofit. The TGDs are a key policy instrument in motivating or changing market behaviour; Gann et al. (1998) established a propensity for building to, or near, the minima of Part L, and the lack of incentives to exceed those minima.[502] Regulations protect the public by creating a minimum baseline, or backstop values (Gann et al. 1998). These cost-optimal findings, therefore, directly influence design strategies for retrofit at a practice level.

"Recent studies point at the unwanted environmental, social and economic impacts of demolition and conclude that lifecycle extension by improvement, renovation and renewal is a better and more sustainable solution" (Crawford et al., 2014, Thomsen and van der Flier 2011, Itard et al. 2006, Power 2010, Thomsen and van der Flier 2009)[503].

Fabric (4 options)	**EE1**	**A**	**B**	**C**
Wall U-value (W/m²K)	0.55	0.39	**0.3**	0.21
Roof U-value (W/m²K)	0.61	0.2	**0.15**	**0.15**
Floor U-value (W/m²K)	0.45	0.15	**0.1**	**0.1**
Window U-value (W/m²K)	3.6	**1.8**	**1.8**	1.4

Services (4 options)	**EE1**	**1**	**2**	**3**
Lighting (lm/W)	25	55	60	**65**

Heating (4 options)				
Heating Source	Gas (74%)	Gas (91%)	**ASHP**	Gas CHP

PV (3 options)			
PV Installation (percentage of foundation area)	0%	10%	20%

Table 5.2: Measures included in cost-optimal analysis for retrofit for office (NV) (AECOM 2015)[504].

AECOM are a private consultancy, hired by the Department of Environment, to interpret regulation EU 244/2012 for Irish cost-optimal nZEB and to apply calculations to an Irish context in 2013. AECOM used the asset life of the measure (fabric – 60 years, windows – 30 years, PV – 25 years, services – 20 years); however, they failed to recognise the remaining lifespan of the existing building pre-retrofit. AECOM ran a series of cost-optimal calculations using a variety of active service packages applied to an EE1[6] median energy consuming building (an

6 • EE1 represents an existing building with a median primary energy consumption.

• EE2 represents an existing building with a 75th percentile primary energy consumption, a more efficient example.

• B is a retrofit measure applied to an existing building including fabric retrofit

existing building complying with Part L 2002). In the calculations, EE1, the base case scenario, was augmented with various service packages. Calculations also included fabric retrofit measures A, B and C (Table 5.2), with various service package upgrades (Table 5.3) (Hermelink et al. 2012)[505]. However, in applying services packages with 20-year lifespan to EE1, no consideration or limitation was given to the existing building's remaining lifespan. In application, this means that a building with a failed envelope can be retrofitted with a service package, without addressing issues relating to the failed envelope. This methodology contradicts the guidelines accompanying Commission Delegated Regulation (EU) 244/2012 of 16 January 2012.

5.9.1 Cost-optimisation and cost-effectiveness

As Aggerholm (2011)[506] succinctly highlights, there is a difference between cost-efficiency and cost-optimality. "A measure or package of measures is cost-effective when the cost of implementation is lower than the value of the benefits that result, taken over the expected life of the measure...Future costs and savings are discounted, with the final result being a "net present value". If this is positive, the action is "cost-effective" (for the particular set of assumptions or the inputs used in the specific calculation). The "cost-optimal" result is that action or combination of actions that maximises the net present value" (Aggerholm et al. 2011). When calculating cost-optimal energy efficiency, we are referring to the measures taken above a minimum baseline over a set calculation period. This baseline could become the minimal level of national building regulations (TGD L 2008).

In 2012, the EPBD provided a Comparative Methodology Framework, including a variety of macro-economic inputs, using scenario analysis (Boermans et al. 2011)[507] to help guide member states to apply cost-optimality calculations for nZEB new build and retrofit in a consistent manner. Kurnitski et al. (2011)[508] offered that the "cost-optimal policy

(See Table 5.2).

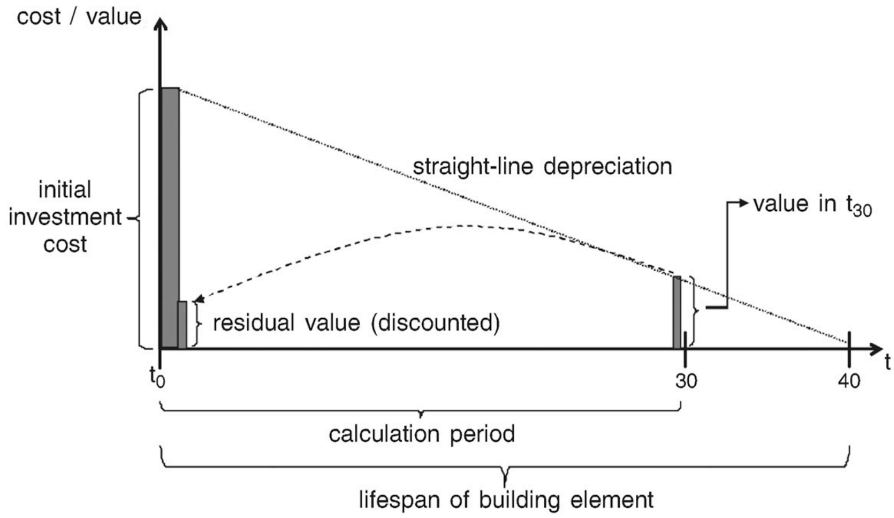
launched by EPBD recast will instruct MS for the first time on how to set minimum requirements and shift those away from only upfront investment cost." In the Comparative Methodology Framework (2012) and other papers, such as Kurnitski et al. (2011), the emphasis was on envelope heat-loss moderation as a key target for energy conservation, "a definition of construction concepts based on building envelope optimisation" (Kurnitski et al. 2011), arising or informed potentially from Passive House methodologies directly referred to in the Guidelines to EPBD 244/2012. The range of inputs includes primary energy consumption cost (kWh/m^2), initial investment cost (€/m^2), operational costs (maintenance and energy consumption), cost of emissions (externalities of CO^2) and residual elemental value (€/m^2) discounted from the investment total, ending in a macro-economic cost of investment. Scenario analysis is run using various elemental packages and strategies. These macro-economic cost scenarios are also run using different central energy price futures and discount rate scenarios (Table 5.3).

Building	Package				PE (KWh/m²)	Initial Investment Cost	Annual Costs		Cost of Emissions	Residual Value	Macro Cost
	Fabric	Heating	Services	PV			Maintenance	Energy			
Retail – 20 year calc	C	ASHP	3	20%	302	240	16	504	26	-31	755
	B	ASHP	3	20%	302	225	16	505	26	-27	745
	EE1	ASHP	3	20%	311	148	16	519	27	-5	704
	EE1	ASHP	3	10%	324	122	15	535	28	-2	698
	EE1	ASHP	3	0%	338*	96	13	552	29	0	691
	EE1	ASHP	2	0%	359	90	13	587	31	0	722
	EE1	Gas (91%)	3	0%	390	66	13	643	35	0	757
	EE1	Gas (74%)	2	0%	431	49	13	711	39	0	813
	EE1	Gas (74%)	1	0%	459	46	13	756	42	0	857
	EE1	Gas (74%)	EE1	0%	652	0	13	1072	58	0	1143
Office (NV) – 20 year calc	B	ASHP	3	20%	95	171	8	165	8	-22	331
	EE1	ASHP	3	20%	124*	80	8	212	11	-2	309
	EE1	ASHP	3	10%	136	67	8	227	12	-1	312
	EE1	ASHP	3	0%	148	54	7	241	13	0	315
	EE1	ASHP	2	0%	152	49	7	248	13	0	317
	EE1	ASHP	EE1	0%	227	26	7	371	20	0	423
	EE1	Gas (91%)	2	0%	252	32	6	422	25	0	486
	EE1	Gas (74%)	2	0%	292	23	6	491	29	0	549
	EE1	Gas (91%)	EE1	0%	316	9	6	527	30	0	573
	EE1	Gas (74%)	EE1	0%	353	0	6	588	34	0	629
	C	ASHP	3	20%	160	258	8	271	14	-41	510

Table 5.3 Macro-economic costs (Central energy price, 4% discount rate, EUR/m^2) (AECOM 2015). Cost-Optimal Additional Calculations and Gap Analysis for recast EPBD for Residential Buildings, Dublin. P. 57.

Aggerholm offers, "Cost-optimality is relatively easy to determine for single measures operating in well-defined conditions" (Aggerholm et al. 2011). However, when multiple macro-economic inputs and discount rates are applied together, calculations become rather more complex and ill suited to everyday use in design practice. Nevertheless, they can play a role informing elemental or whole-building performance regulations, although it is particularly hard to quantify the impact of the results on air quality and thermal comfort (Ascione et al. 2015)[509].

In Table 5.3 (highlighted in yellow) we see that package EE1 (no fabric retrofit) for a naturally ventilated office, including an active service, results in a primary energy consumption of 124 kWh/m^2, at an initial investment cost of €80/m^2, amortised over a 20-year calculation period, with a residual value of the service elements of €2/m^2 at the end of the calculation period. This results in the lowest positive macro-cost (€309/m^2), with the lowest residual value (-€2/m^2) when compared to Option B with a macro-cost of €331/m^2, 9% more expensive over the calculation lifetime, but a significantly greater residual value (-€22/m^2- implying the building fabric has a longer lifespan). While Option B (fabric retrofit) has an initial investment four times that of EE1, with 22% greater operational energy saving (with analogous GHG abatement savings) over EE1 on the 20-year lifespan, it is not as cost-optimal as the active based solution applied to the EE1. We can see the residual value of Option B is -€22/m^2, meaning that after the calculation period there is a remaining net present value which can be discounted from the original investment cost. However, there is no reference to whole-building condition or net present value of the existing building at the beginning or end of the calculation period, nor is there any transparency to the impact of any of the options on thermal comfort or air quality, as referenced in the guidelines to EU 244/12.



Graph 5.10 Calculation of the residual value of a building element, which has a longer lifetime than the calculation period (EU Directive 244/12).

MS-modelled packages for retrofit should be "determined by the so-called refurbishment cycle of a building" (EU 244/12). Figure 1 assumes a building lifespan of 40 years, highlighting a cost-optimal calculation period of 30 years for a public building. Where a public building's cost-optimal calculation is spread over 30 years, the residual value of the remaining 10 years of lifespan is discounted from the cost of the retrofit package at the beginning of the calculation period. "The residual value of a building at the end of the calculation period is the sum of residual values of all building elements" (EU 244/12).

The initial AECOM cost-optimal calculations (AECOM 2013)[510] had to be revised in 2015, with additional calculations (AECOM 2015)[511] for retrofit. Both reports simulate different retrofit packages on 5 different reference buildings. "This kind of analysis cannot be applied to each single building, and, therefore, a set of Reference Buildings (RBs) must be defined in order to represent the national stock" (Ascione et al. 2015)[512]. The sample of reference buildings are limited to Retail, Office (AC), Office (NV) and Hotel, all of which are calculated at a 20-year lifespan, and a primary school (Public), which is calculated at a 30-year lifespan. By comparison, a concurrent UK report uses a secondary school and a hospital as public reference buildings to provide a basis for a 30-year macro-economic analysis. However, Member States were required to "define reference buildings that are characterised by and representative of their functionality and geographic location, including indoor and outdoor climate conditions. The reference buildings shall cover residential and non-residential buildings, both new and existing ones." It could be argued that to choose a single functionality, with a particularly low level of services, and unique occupancy profile would not be characteristic of the full range of retrofit building stock. "This arbitrary element in picking reference buildings might be a source for deviations and inconsistencies in the comparison" (Aggerholm et al. 2011)[513]. By comparison, (Table 5.4) UK reference buildings provide a more representative selection of energy-intensive public buildings (with a greater amount of equipment), offering varied annual occupancy rates (24-hour and 365-day occupancies for the hospital) and thus, more accurately reflecting existing energy demand, which is comparable to average energy usage in buildings (CIBSE 2008)[514].

Complying with EU 244/12 (6.7), UK and Irish reports discount elemental residual values (remaining lifespan after the calculation period) from front-end investment costs (Graph 5.10). The UK analysis uses a 3.5% discount rate for macro-economic calculations, which is more favourable to energy efficient strategies than the higher Irish Discount rate of 4%; "Higher discount rates devalued (and thus, effectively lowered) the price of energy over the calculation period and thus, tended to favour less energy efficient products" (UK Department for Communities and Local Government 2013)[515]. The UK report acknowledges the issues of building lifespan by including fabric retrofit measures as a baseline for analysis, and creating a median solution across reference buildings with more representative reference stock. The UK report takes an elemental approach, using 15-year old case studies for buildings' energy benchmarks for EE1 and EE2 (EE2 being the better energy performance stock: 75th percentile).

Reference Buildings for Existing Buildings

UK

Building Category	Energy Efficiency Level	Construction type	Typical energy performance $kWh/m^2/yr$	Component level requirements
Office (NV)	EE1	Steel Frame	347	The relevant component level standards for existing non-domestic buildings are included in Table 3.2.
	EE2	Steel Frame	242	
Secondary School	EE1	Cavity Wall	302	
	EE2	Cavity Wall	243	
Hospital	EE1	Steel Frame	604	
	EE2	Steel Frame	513	
Hotel (AC)	EE1	Steel Frame	880	
	EE2	Steel Frame	741	
Retail Warehouse	EE1	Steel Frame	521	
	EE2	Steel Frame	475	

Ireland

Building Category	Energy Efficiency Level	Construction type	Typical energy performance $kWh/m^2/yr$	Component level requirements
Office (Natural Ventilation)	EE1	Cavity Wall	412	Refer to appendix A
	EE2	Cavity Wall	331	
Office (Air Conditioned)	EE1	Steel Frame	505	
	EE2	Steel Frame	393	
School (Primary – Natural Ventilation)	EE1	Cavity Wall	202	
	EE2	Cavity Wall	105	
Hotel (Air Conditioned)	EE1	Cavity Wall	677	
	EE2	Cavity Wall	515	
Retail (Air Conditioned)	EE1	Steel Frame	859	
	EE2	Steel Frame	659	

Table 5.4 EE1 & EE2 baseline comparisons of energy consumption UK & Ireland (AECOM 2013)

Baseline EE1 energy consumption for Irish office buildings (NV) (Table 5.4) is 16% higher than UK counterparts, and 48% higher than CIBSE TM46 (2008) guidelines. EE1 values for retrofit (2002 and 2008) (wall 0.55 W/m^2K, roof 0.61 W/m^2K, floor 0.45 W/m^2K and window 3.6 W/m^2K) would suggest the EE1 has poor average fabric performance (similar to that of Irish Draft Building Regulations 1976 and not dissimilar to existing retrofit regulations), requiring a higher heat demand to maintain thermal comfort in heating season. The reports find that the cost-optimal primary energy consumption level for a naturally ventilated office building retrofit is 89 kWh/m2a (UK) compared to 124 kWh/m2a (Ireland). Unlike the Irish report, the UK report does not give a whole-building performance value, making a comparison less transparent.

The sample selection of reference buildings in both reports does not take account of the remaining building lifespan, as noted in the EU 244/12 guidance. Basing the UK EE1 baseline on 15-year old ECON guides does ensure an older selection set, but may under-estimate energy consumption, as a result of deteriorating building fabric over the intervening years. Both reports take a component-level approach rather than a performance-based approach, as "it is most common to retrofit building components independent of each other, and national standards for existing buildings (Table 5.5) are based on a building component level" (DCLG UK 2013).

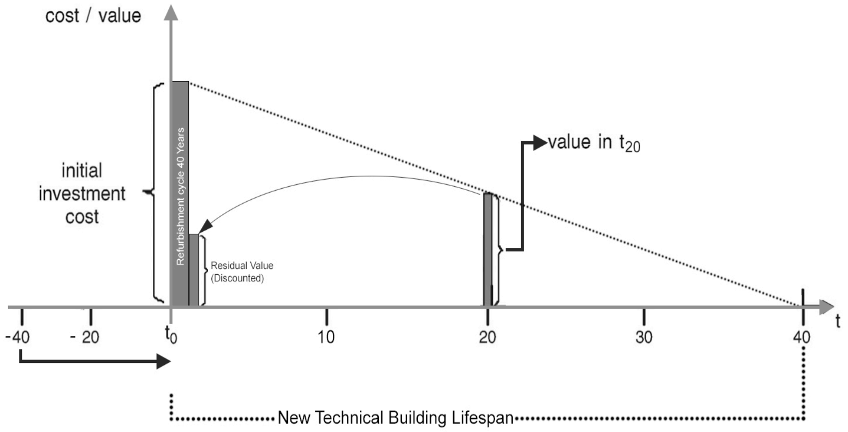
Fabric (3 options)	RTC 74	Part L 2002 Retrofit	Part L 2008 New Build	Ireland Cost Optimal nZEB **New Build** Option EE1	Ireland Cost Optimal nZEB **Retrofit** Option EE1	UK Cost Optimal nZEB **Retrofit** Option EE1	Alternative Cost Optimal Option B standard for retrofit	Zero2020
Wall U-value (W/m^2K)	1.2	0.60	0.27	0.21	0.55	0.3	0.21	0.1
Roof	1.4	0.35	0.22	0.2	0.61	0.25	0.2	0.1
Floor U-value (W/m^2K)	0.42	0.60	0.25	0.2	0.45	0.25	0.2	
Window U-value (W/m^2K)	5.6	2.20	2.2	1.4	3.6	1.8	1.4	1
Improved Thermal Bridging		YES	YES	YES	NO	NO	YES	YES
Air Tightness ($m^3/m^2.hr$ @ 50 Pa)	15	10.00	10	5	15	7	5	1.67
Services-Elec				65 lm/W	65 lm/W	55 lm/W	65 lm/W	65 lm/W

Table 5.5 Comparison of cost-optimal targets, existing building (RTC 74), regulations, cost-optimal nZEB and measured ZEB retrofit (Zero2020).

Some inconsistencies are noticeable in the comparison of both reports. The reference buildings and cost-optimal methodology application within the Irish calculations do not acknowledge the remaining whole-building lifespan of the existing building, with the EU assuming a technical whole building lifespan of 40 years (and UK assuming 60 years). The Irish report, thus, provides for an optimum case scenario for service solutions retrofit, where the reference buildings have an optimal remaining lifespan of 20 or 30 years. This deviation from, or interpretation of, the guidelines would appear to contradict the intent of EU 244/12 on two central issues: firstly, the existing building's remaining technical lifespan is either not considered, as the reference building has not reached its "refurbishment cycle…which is the period of time after which a building undergoes a major refurbishment" (EU 244/12), and secondly, Irish calculations only value the residual value of retrofitted elements at the end of the calculation period and not the "sum of all building elements" (EU 244/12). Reference building cost-optimal calculations, thus, ignores the impact of fabric and elemental degradation on remaining building lifespan and net present value.

AECOM confirmed, “The actual building life is not discussed in the Cost-Optimal Methodology. Rather, we only consider the calculation period (either 20 or 30 years) and the asset life of the measure (fabric – 60 years, windows – 30 years, PV – 25 years, services – 20 years). The residual cost only applies to the package. We do not consider the whole building, since these are costs that also affect the counterfactual” (Pountney 2015) [516]. Pountney (2015) is, therefore, saying that the savings made by service-based measures are more straightforward to calculate, in a counterfactual- “business as usual” scenario (Hull, Ó Gallachóir and Walker 2009)[517].

However, Delegated Regulation (EU) No 244/2012 clearly states in section 6.6: “besides initial investment costs and running costs, periodic replacement costs are the third cost driver. Whereas smaller repair work and consumables are usually subsumed under maintenance costs, periodic replacement refers to the necessary substitution of a whole building element as a result of ageing, and is therefore treated as a separate cost category. The point in time of periodic replacement depends on the lifetime of the building element. At the end of that lifetime a replacement has to be provided for in the global cost calculation” (European Parliament 2012)[518]. The lifespan of the existing building fabric or a service package intervention (like a heat recovery unit with a 15-year lifespan) have consequent cost impacts during the calculation period that are not being reflected in the Irish calculations. Thus, the Irish Reports of 2013 and 2015 appear to be biased towards lower capital-intensive cost strategies: service-based strategies. “In all cases the cost-optimal package has no fabric improvements…improving fabric can lower primary energy demand, but it is expensive” (AECOM 2015). The UK report (which is elementally-based) finds that fabric retrofit is cost-optimal, even in the context of much lower U-Values, when we compare the existing Irish regulations (2002) and UK cost-optimal (EE1) in Table 5.5.



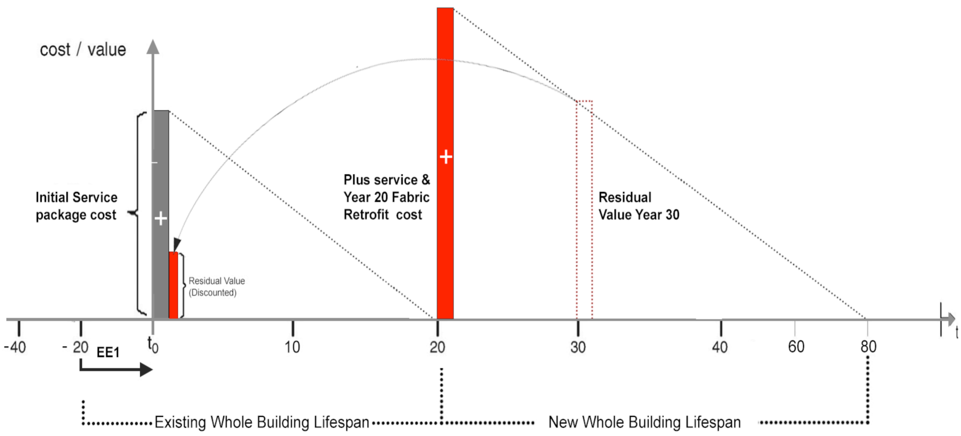
Graph 5.11 Calculation of the residual value of a building element, which has a longer lifetime than the calculation period (European Parliament 2012)

Whilst there is no doubt that active systems with high coefficients of performance (COP) can deliver lower heating and lighting costs, they will not address the substantive issue of the building fabric lifespan or space heating demand. Thus, calculation period should be limited to either:

a. The remaining whole building lifespan of the existing building (could be technically difficult to do as a reference building).

   <u>or</u>

b. Increasing the whole building lifespan with the supplemental cost of a fabric retrofit, less the discounted residual value at the end of the calculation period. (Graph 5.12)



Graph 5.12 Augmented calculation of the residual value of whole building, which has a longer lifetime than the calculation period.

Unfortunately, EU 244/12 could expound in greater detail on the treatment of the existing technical lifespan of the whole building, in the context of retrofit nZEB cost optimal calculations. Figure 3 illustrates a proposed resolution in straight-line depreciation for a public building with a 30-year lifespan. An EE1 service package is replaced after 20 years, plus a fabric retrofit and added to the initial investment cost. This initial investment cost is now the basis for cost-optimal calculations to be amortised over the calculation period of 30 years.

5.9.2 Findings

The physical issues with augmenting a deteriorating building with an Irish EE1 technical and service-based solution is that the service package may not fully address indoor environmental issues such as IEQ and radiant thermal asymmetry, which will remain a problem with a deficient envelope; moreover, poor air quality cannot be addressed in a naturally ventilated building by the use of ASHP or more efficient lighting. The EU Parliament has accepted the Irish cost-optimal nZEB report, and its recommendations are likely to influence the standards of Part L 2017(Armstrong 2015)[519]. However, the macro-economic analysis demonstrated on a 9% spread in costs over Option B (Table 5.8) which, if adopted as in Part L would demonstrate an equivalent standard to new build, making the regulations simpler to understand and more homogenous.

These findings were presented as part of a paper to the Department of Environment, who accepted in principle the validity of the analysis, with further assessment required from AECOM, which is unlikely to happen before the publication part L 2017 for public consultation (Armstrong 2015)[520]. This research will become part of a detailed response to the public consultation process due in spring 2016.

5.10 Conclusions

The building regulations since 1976 have steadily tightened and improved energy conservation in buildings (Table 5). The EU has realised that national regulations must be informed, not only by the internalities of capital costs, but also the externalities of CO^2 emissions and their impact on GHG emissions.

The transposition of EPD 2002 and EPD 2010 (recast) ushered in improved mandatory building energy regulations for new buildings, leading to the construction of A-rated homes as a standard. Strengthening standards increased in complexity, moving architectural practice away from backstop elemental values and overall heat loss methods, towards performance oriented compliance. Rising levels of non-compliance with Part L may be flagging practice or system problems in applying or realising the standards in construction. The increasing requirement for building performance assessment tools to achieve compliance is disadvantaging architects who have a low level of BPS usage. This highlights training and knowledge gaps, which could impact the adoption of NZEB retrofit. Passive House training indicatively improves the uptake of BPS tools amongst architects.

Low-energy building performance is increasingly dependent on a systematic approach to architecture, where the design of the structure, envelope and services are interdependent parts of the building energy performance post-occupancy. This requires a greater level of communication and simulation during the iterations of the design. Therefore, practice needs to move to a more integrated interdisciplinary collaborative paradigm to deliver post-occupancy NZEB performance.

Building energy certificates, retrofit grants and rising oil prices helped drive market demand for low-energy retrofit to almost 100,000 units per year in 2011 (Graph 5.6). However, the recession, changing government priorities, a lack of financing, falling grants and falling oil prices led to

what is potentially a market failure in retrofit. The Irish government's retrofit policy diffusion sees it only achieving 10% of its intended annual dwelling retrofit target.
There is an investor focus simple payback methods which bias towards light retrofit options primarily because of shorter operational cost saving payback periods with investvest barriers to deep retrofit including variable interest rates, volatile energy costs, the lack of energy auditing, and the lack of post occupancy measurement and validation.

The EU has highlighted that Ireland is under-performing in GHG abatement targets and the EPA has warned the government that they will miss their GHG 2020 targets by a margin of 40%-75%. The Taoiseach (Prime Minister) accepted that Ireland would miss its 2020 emission targets. Serious changes in government policy diffusion are required across a number of sectors to ameliorate this position. In the context of NZEB retrofit, market failures, a lack of revised mandatory legislation since 2008 and collapsing oil prices are seriously impacting the potential for this sector to contribute to GHG abatement. Revisions to new building energy regulations in 2011 shift market behaviour resulting dramatic increase in A & B rated energy efficent homes. Carbon dioxide emissions for the car industry in Ireland fell as a result of linking emissions to car tax in 2008 (Hennessy & Richard 2011)[521]. Both cases demonstrate that effective regulation and tax measures can shift market behaviour.

The proposed amendments to Part L 2017 will be heavily influenced by the cost-optimal nZEB calculations. Their recommendations for no fabric retrofit and no changes to the retrofit elemental standards, as outlined in Part L 2008 and Part L 2002, will impact the potential for GHG emission abatement in this sector, and potentially change best practice towards services (mechanical and electrical systems) only retrofits. Given the similarity of the Part L 2008 standards to the 1976 elemental standards, it is clear that there has been historical low policy intensity towards the regulation of building retrofit in Ireland. Ireland as a result, will develop, as Fraunhofer and Ecofys (2010) define it, a moderate technical scenario for future retrofit regulations, where cost effective measures are included but costly external fabric upgrades are excluded. Thus, in response to research question 3, the transposition of the EPBD regulations into Irish building energy Regulations are unlikely to result in high policy intensity scenario, as defined by Fraunhofer and Ecofys in 2010.

Serious concerns have been raised here with the Irish cost-optimal calculation methodologies. The Irish cost-optimal calculations do not use a representative reference public buildings, in terms of occupancy or energy intensity, they fail to acknowledge the role of remaining whole-building lifespan at the beginning of the calculation period and they fail to make transparent the environmental consequences of retrofit packages (as required by the Cost Optimal Regulations 2012), whilst recommending no fabric retrofit for cost-optimal nZEB. TGD Part L 2017 is, therefore, likely to be driven by improved elemental service packages, rather than improved envelope performances, thus having implications for future nZEB or NZEB design practice. If this were to happen, the potential for 80% GHG abatement through the retrofit of 1960s and 1970s buildings would remain unrealised. These research findings have informed representations to amend the draft Part L 2017 regulations, prior to their public consultation period and the research will also inform this public consultation period in mid 2016.

It is worth noting that cost-optimal calculations and existing regulations do little to value the CO^2 related emissions with end of life of building materials. Indeed, boundary issues do not reflect the full cost-of-life cycle carbon in the construction cycle. Whilst we have addressed some of the embodied energy issues in reusing a building through retrofit, life cycle analysis is beyond the scope of this study.

Ireland would appear to have both a low regulatory intensity for energy conservation in buildings, and a low level of compliance. Architects may be over dependant on “acceptable construction details”, and there appears to be a low level of simulation use in architectural praxis. Indeed, 60% of architects feel they are not ready to deliver on nZEB performance. Design team communications appears to be another issue impacting energy performance, as well as legislative boundary issues with fixed and plug loads. With Ireland facing a 40%-75% gap to achieving Kyoto GHG emission commitments by 2020, the government and praxis appear to be poorly placed to improve this position through nZEB retrofit. That said, it is still one of the most cost-effective ways of achieving emission abatement targets… and yet, the existing poor level of retrofit energy regulation may be set to continue, if cost-optimal recommendations are followed through into the revision of Part L 2017.

In the following chapter we examine the impact of changing regulations on Regional Technical College retrofit case studies, across a period of 14 years. The *Process Domain* stage will examine client priorities and the impact of regulations on building energy performance targets. It will assess passive and active strategies, looking at the use of simulation, cost-effectiveness, design solutions and design team relational networks.

CHAPTER 6

CASE STUDIES OF RTC BUILDING RETROFITS

Chapter 6: Case Studies of RTC Building Retrofits

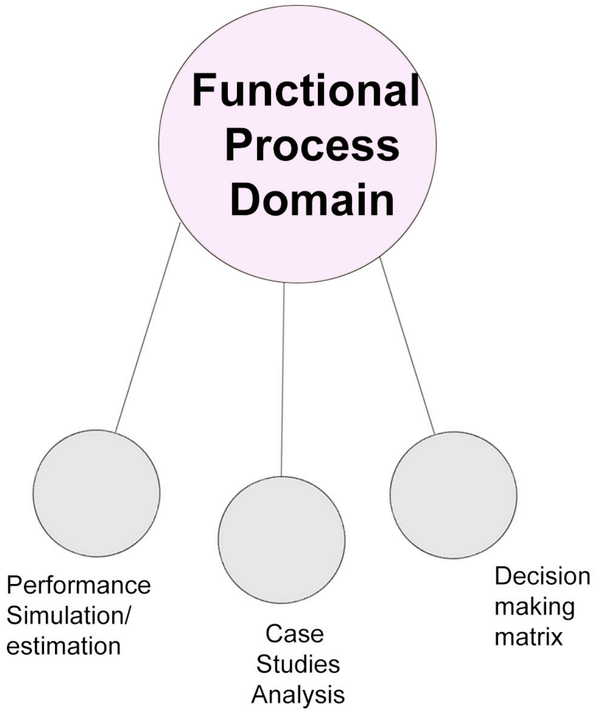
1.1 Background

The previous chapters examined the legislative context, within which retrofits to various Regional Technical Colleges were carried out from 1998 to 2011. "Before the impacts of energy efficiency programs and policies can be estimated, accurate measurements and understanding of the base condition is essential" (Horowitz 2007)[522]. The following chapter examines the existing precedents of RTC buildings (1998-2012), where, when and why retrofit methodologies were applied; also, whether they were successful at reducing energy demand, examining strategies, problems, client decision-making priorities, use of simulation and scenario cost analysis. The cases studies are examined to establish the priorities driving decision-making, what energy conservation measures (ECMs) are employed, what stages are included in the socio-technical process and what errors or faults arise. This examination leads to a mapping of optimal processes for energy performance outcomes and a comparison of ECMs adopted in a comparative cross case analysis.

6.1 Methodological Statement - Process Domain

Case study analysis falls under the functional and process domain. The case studies selected are a heterogeneous set of retrofits to a homogeneous typology. Different strategies for the retrofits of the same building typology illustrate both different priorities over a period of 13 years and 3 different sets of building energy regulations. The case studies allowed the researcher to also question the process of decision-making, relating this to operational energy saving and ECM selection. Therefore, the case studies also reference aspects of the *'Formal and Normative Domains'* in discussing and analysing the use of scenario analysis.

Where change is the steady state of practice changes to the RTCs, over time, contextualise the multivariate priorities of stakeholders, demonstrating both technological and contextual responses. Stage 6 presents comparative cross-case research studies of architectural solutions and related decision-making, in the planning and realisation of RTC retrofits over a 13-year period (1998-2011). Case-based research is the cornerstone of the reflective practice (Schön 1982)[523], thus this stage used the case studies to understand how stakeholder priority and relational networks change as a result of external and internal forces.



Graph 6.1 Domain Stage 6 - Process Domain and Domain Stage 7 - Functional Domain (Ó Riain 2015).

The primary research involved a detailed search of original construction drawings and specifications from 1968, unpublished design stage proposals for retrofit, a detailed survey of the existing case study buildings to record and resolve variations, reporting on intervention strategies, interviews with the original architects, engineers, local stakeholders and current building operators, including the simulation modelling of proposed and existing façade details. This is done to attempt to establish a baseline of evidence, highlighting risks, and developing optimal processes to inform retrofit methodologies and to use precedent reports as part of an action research reflective design (Schön 1973][524]. The outcome of this research will inform a pilot-project reported in the next chapter.

Dewey (1916) began to define the reflection on practice, to elicit what lies between our actions, to find the "cause and effect, activity and consequence. This extension of our insight makes foresight more accurate and comprehensive" (Dewey 1916)[525]. Schön argued that the reflective practitioner can "criticise the tacit understandings that have grown up around the repetitive experiences of a specialised practice, and can make new sense of the situations of uncertainty or uniqueness which he may allow himself to practice" (Schön1973)[526]. Kuhn (1977) highlighted the importance of valuing the old, to inform new discovery, and urges us to "begin, by learning a good deal of what is already known" (Kuhn 1977) [527].

Having explored the explicit knowledge codified in regulations, this domain stage broadens the understanding of retrofit practice through case studies of various RTC refurbishments, to try to elicit "experienced based" and "tacit knowledge" (Polanyi 1966)[528]. We have examined the external factors, which influence policy diffusion and the adoption of low-energy strategies in retrofit, and the variation of priorities that influence that adoption. Now, we examine the internal factors, to thoroughly analyse the "negotiation between problem and solution, through the activities of analysis, synthesis and evaluation" (Lawson 1980)[529].

6.2 Case Study Methodology

As Garvin (2003) records, *Case Method* has long been used at Harvard University in traditional disciplines such as law, medicine and business. "Case studies often serve to make concrete what are often generalisations or purely anecdotal information about projects and processes" (Francis 1999)[530]. Johansson (2003) contends that case studies should be the object of study. They should

- *Be a complex functioning unit,*
- *Be investigated in its natural context with a multitude of methods, and*
- *Be contemporary.*

(Johansson 2003)[531]

"As a form of research, case study is defined by interest in individual cases, not by the methods of inquiry used" (Stake 1995)[532]. The Regional Technical Colleges are a limited subset of common precast concrete buildings built in Ireland in the late 1960s and early 1970s. They have been refurbished at various locations since 1997. Their educational functions fall into the "non-dwelling" subset of regulations, having to comply (at the time of retrofit) with Part L, 1997, 2002 or 2008 (as far as practically possible). They are regionally located at 8 campuses, and are complex, functioning, architectural artefacts, approaching the end of their initial lifespan. Different methods were used in the research of each case study to collect evidence from primary sources, including: site visits, surveys, drawings, measurements, recordings and interviews with original designers and current stakeholders. Unpublished data was accessed, in the form of internal government reports, declassified documents, feasibility studies, energy performance reports, energy consumption data from service bills, original drawings and specifications. Published secondary data came in the form of official reports, regulations, grant schemes and published industry articles. There was very little in the way of published information on the retrofits of the RTC buildings, therefore most of the data collected is originally sourced material. This was done to establish a baseline of evidence to inform retrofit methodologies and to use precedent retrofits as part of an action research reflective design cycle (Schön 1982)[533]. Individual project reporting is to be found in Appendix 6, with analysis of this data included in this chapter. The outcome of this research helped inform the development of an 'outline' socio technical process for performance oriented retrofit in Ireland which will be tested in pilot-project reported in the next domain stage.

The case studies are current, representing existing strategies, reflecting decision-making protocols, demonstrating the priorities of the stakeholders and relational networks. The potential for the energetic retrofit of 109,000m^2 over 8 sites could provide an exemplar to industry, in the context of nZEB retrofit standards and EPBD 2010 implementation. However, their potential to achieve nZEB or NZEB[7] standard performance through retrofit had not yet been established.

6.3 Introduction: Case Studies

The purpose of this domain stage was to study the existing retrofit strategies to the RTC typology over a 14-year period and to examine client priorities, design solutions, potential problems and advantages with various solutions. The research also sought to clearly describe the potential of various retrofit solutions to contribute towards nZEB or NZEB performance, through retrofit, highlighting potential solutions and problems with case study strategies.

[7] An nZEB is a nearly Zero Energy Building with a balance of energy consumption yet to be met by site renewable energy. An NZEB is a Net Zero Energy Building where the energy balance has been met by site renewable energy.

Reference to various blended sources of information compensates for individual biases and efforts are made to base reports, as much as possible, on objective and observable facts. Reporting, included in Appendix 6, was broken down into the following headings for a structured comparison:

1. Massing and scale,
2. Building envelope design,
3. Building services,
4. Energy efficiency actions,
5. Retrofit actions,
6. Findings.

Drawing on the reporting a cross case comparative analysis examines priorities, processes, energy conservation measures (ECMs), energy performance, issues arising, flaws and learning outcomes. Analysis includes commentary on goal setting, the level of decision-making, relational networks and process continuity. This analysis provides an opportunity for reflection on the facts, to extract "reliable knowledge… and communicate re-usable results", for both the design phenomenology and design praxeology (Cross 2006)[534]. Findings contribute to an expanded list of barriers to nZEB retrofit in Ireland. These barriers are broken down process, disciplinary and decision-making barriers and compared to global barriers identified in chapter 1. Process improvements to address these barriers are into synthesised into an optimal process map for low energy retrofit, drawn from the cross case comparative analysis of processes and ECM adoption.

6.4 Case Study Sample Selection

The selection of case study buildings was relatively straightforward. All significant RTC retrofits and proposed retrofits over a 14-year period were selected, while noting the retrofit of the related precedent building at Birmingham in 2010 and 2011. The researcher retrospectively examined the RTC typology building retrofits over the 14-year period, predating EPBD 2010, tracing the guidelines of Irish Building Regulations up to TGD Part L 2008. The reporting (in appendix 6) excludes the pilot-project retrofit, Zero2020 at Cork Institute of Technology (CIT), which is addressed in Domain Stage 7, but findings from conditions surveys and building performance analysis can be found in this section of the study. The various building retrofits demonstrate how client attitudes can change when presented with simulation and scenario analysis, how risk analysis can be used in the socio-technical process, highlighting the lack of post occupancy analysis in practice, and the lack of iterative learning outcomes with repeated errors from project to project. Case studies illustrate the movement of client priority towards energy conservation, exceeding the minimum level of compliance with building regulations, where cost benefit analysis begins to play a greater role as a driver of decision-making. Throughout the reporting we will find that design team proposals, using simulation and scenario analysis, aid client capital investment decision-making, resulting in design stage energy performance targets which are 27%-33% beyond the minimum standards of new building regulations.

Process Domain case study buildings:

1. Waterford RTC 1998
2. Athlone RTC 2000
3. Letterkenny RTC 2002
4. Dundalk RTC 2005 (Report)
5. Carlow RTC 2005-2011
6. Ó'Fiaich College 2006-2007
7. Galway RTC 2008
8. Cork RTC 2010 (Report)
9. M&M building Birmingham 2010/11
10. CIT Phase 1 (Zero2020), Cork RTC2012
11. CIT Phase 2, Cork RTC2012

Case study reporting is included in Appendix 6. Of the case studies included in the cross case comparative analysis, Waterford (1998), Letterkenny (2002), Dundalk (2005), Carlow 2005, Ó Fiaich College 2006-2007 and the Cork retrofit master plan in 2010 are the most relevant due to:

a. The level of reporting
b. Casual differences between cases
c. Different regulatory environments
d. Similarities and differences in strategies and ECMs
e. The level of evidence available

6.5 Report on RTC Retrofits

The case study buildings represent retrofit iterations, and their examination provides opportunity for reflection and conceptualization in the cycle of experiential learning (Kolb 1984)[535].

6.5.1 Precedent RTC retrofit reports

A series of retrofits were carried out over 13 years at a number of the RTC buildings. During some of these refurbishments, unpublished reports were commissioned to establish location-specific retrofit methodologies, which sometimes demonstrated a commonality, iteration and development of previous retrofit solutions across a number of RTC campuses, from Waterford 1997/8, Letterkenny 2002, Carlow 2005 & 2010, Dundalk 2005, Ó Fiaich College 2007/8 & 2011 and CIT 2011.

In some cases, capital funding, energy consumption targets, new building regulations, software simulations, scenario analysis and return on investment calculations were key factors informing client decisions on retrofit strategies (Letterkenny 2002, Dundalk 2005, Cork 2010). In other cases, no such detailed analysis was found to inform decision-making on retrofit strategies, and decisions were, as a result, more arbitrary (Waterford 1998 and Carlow 2005). In some cases, reports were commissioned but no works were carried out (Dundalk 2005, Cork 2010)

(Many of these reports are very bulky, not suiting physical inclusion in Appendix 6. However, these are available on the link to Appendix 6.2)[8].

Almost no post-occupancy analysis exists from the RTC retrofits from 1997 to 2010 and much of the post-occupancy commentary is based on un-quantifiable subjective opinion from interviews. However, one report from Semple McKillop (2012)[536] on Ó Fiaich College highlights post-occupancy energy performance, which can be compared to design stage reports from Dundalk. Critically, they demonstrate that where detailed design stage reporting is employed, using simulation and scenarios, it often resulted in clients' shifting design energy performance priorities to exceed the minimum requirements of the building regulations. The researcher has reviewed the unpublished reports, carried out primary research, surveyed the different locations, and compared the development strategies, highlighting variations and priorities in this document.

[8] https://www.dropbox.com/sh/ttsukmznroowach/AACInUKpdLUGIisFlWsSHYvoa?dl=0

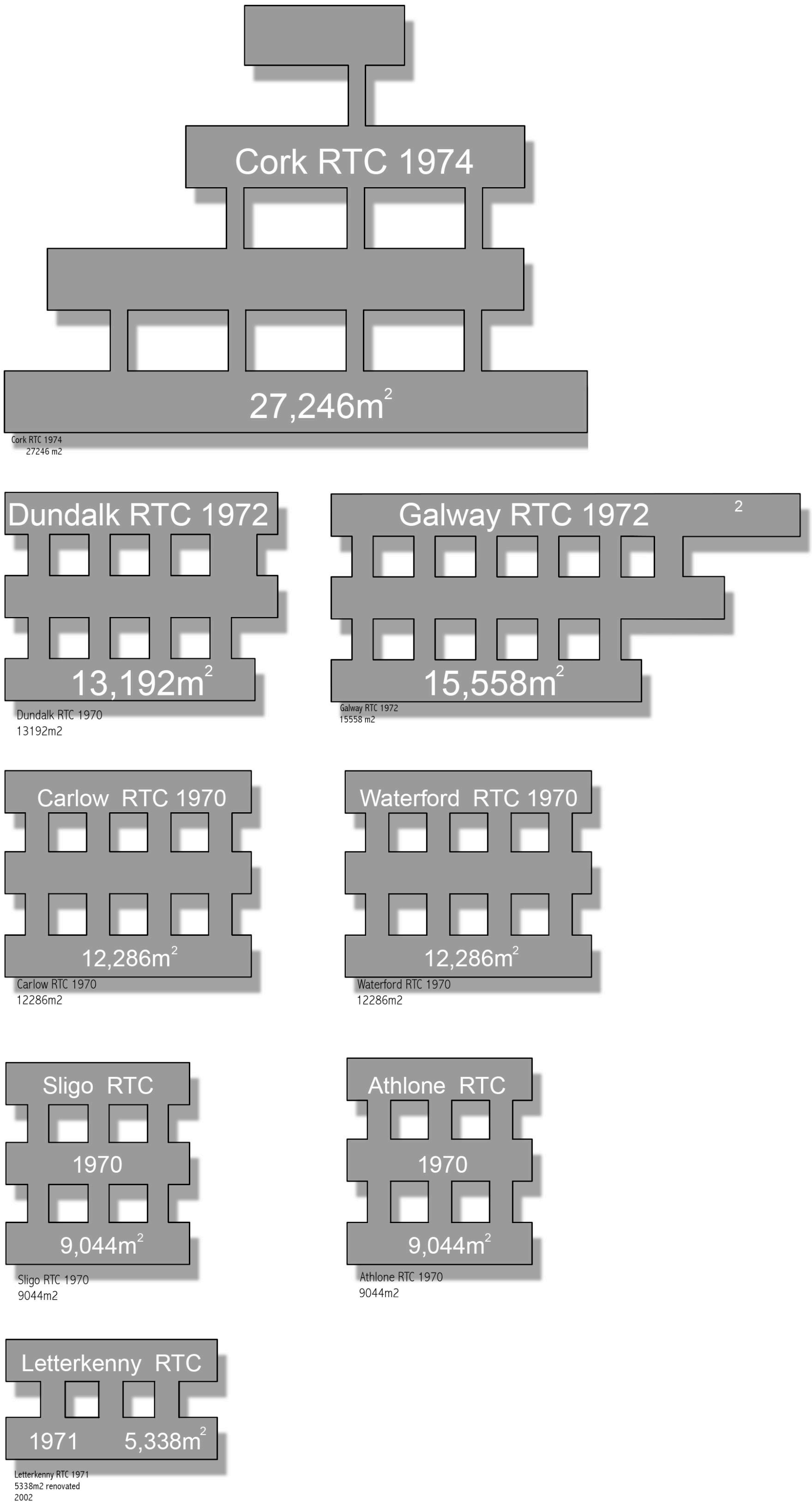


Fig. 6.1 RTC Typology: Massing and Building Areas. Note the scale change for Cork, which led to double-loaded blocks with classrooms either side of a central corridor (Ó Riain 2015).

6.5.2 Redevelopment Timeline

A series of retrofits were planned and or carried out at RTC locations over the years since the construction of the buildings at 10 campuses (1969-1974). In 3 locations, an additional lightweight floor was added, establishing the potential for vertical expansion, and confirming evidence of the same capability from the 1968 *Preliminary Report* on the RTCs (Department of Education 1968)[537]. Various sites upgraded their envelopes to various extents, from decoration and joint sealing, to over-cladding, including either internal or external insulation. Many of the RTCs upgraded their windows, either fully or partially, to double-glazing at some stage, and a few have insulated roofs. A variety of interventions were made on the interiors such as enclosed quads, new partitioning, new drop ceilings, and floor coverings. In most cases the existing radiator system still exists, with Thermostatic Radiator Valves (TRVs) installed locally at some locations. Service upgrades have occurred, with the most popular being lighting upgrades with occupancy sensor controls, followed by the replacement of heating system boilers, and the use of combined heat and power systems (CHP). Renewable energy production (Wind and/or PV) is in place on a number of sites, with none feeding back into the grid (no feed in tariff). The research involved the reporting of all retrofitted RTC sites (appendix 6), but a selection are compared and analysed here, where there was a greater amount of evidence available, and where they can be related in some way to each other in some way. (Table 6.1)

Sequence of RTC Retrofit/new build Developments		
RTC Location	**Year**	**Action**
Cork RTC	1985	Quad infill
Waterford RTC	1995	Quad infill
Letterkenny RTC	1995	Added third floor
Waterford RTC	1997/98	Added third floor
Carlow RTC	2000	Quad infill
Waterford RTC	2002	Upgraded envelope
Letterkenny RTC	2002	Upgraded envelope
Carlow RTC	2005	Upgraded envelope
Dundalk RTC	2005	Feasibility report
Ó Fiaich College	2008-2010	Upgraded envelope, Services, PV
Cork RTC	2010	Feasibility report
Carlow RTC	2011	Added brise soleil
Cork RTC	2012	nZEB pilot project
Cork RTC	2012/13	New build

Table 6.1 Sequence of RTC redevelopments 1985-2013 (Ó Riain 2016)[538].

6.5.3 Linking the retrofits

Letterkenny RTC added a lightweight third floor in 1995, followed by one in Waterford in 1998, and another in Athlone in 2000. Although the design teams were different, they all used a similar lightweight structure in adding one floor. Despite these precedents and the same typology, ARUP reported in 2011 that a third floor was not possible at Cork Institute of Technology (CIT) due to loading factors, but had included a third floor in its strategic retrofit master plan report (2010) for the CIT retrofit.

External fabric upgrades varied from rendered/painted finishes at Galway and Waterford, with aggregate panel joints sealed, to external ETICS[9]

[9] *External Thermal Insulation Composite Systems*

render system insulation at Carlow, Letterkenny and Ó Fiaich College and brick cladding at Athlone RTC. The same ETICS render system and architectural detailing was proposed for the CIT Master plan in 2011. The feasibility report for Dundalk directly informed the Ó'Fiaich College retrofit strategy (McGovern 2015)[539], which in turn informed the Cork retrofit master plan feasibility report in 2010 (McCann 2012)[540]. All three projects involved the same architects, but different engineers.

Many of the RTC case studies changed from original single-glazed aluminium framed windows, to sealed double-glazed aluminium framed windows (Letterkenny, Waterford, Athlone, Carlow and Ballinode College Sligo), with original windows remaining in place in Cork and partially in Galway (75%) (Lee 2015)[541]. Letterkenny added shading devices over south-facing windows in 2002, followed by Ó Fiaich College in 2008, but Carlow installed them in 2010/11 for aesthetic purposes on the north and west faces (Hassett 2015)[542].

The same architects carried out the fabric upgrades to Waterford (1998) and Carlow (2005) (Howley 2015)[543]. Ó'Fiaich College, which is located adjacent to the original Dundalk RTC campus and is of a similar typology, was retrofitted between 2006 and 2010 to a higher standard than any of its precedents, directly informing the goals for Cork RTC retrofit master plan (2010). In 2011, the Mining and Metallurgy Building at Birmingham University, which was the original precedent design for the RTCs, was renovated by Arup, who were also the engineers to all the original RTCs and engineers on the Cork RTC feasibility study (2010). These cases would all become interlinked, some strategies becoming iterations for the subsequent RTC retrofits, and some strategies abandoned at report stage primarily due to lack of funding. Other, new building works were carried out around these original buildings on the various sites, but their impact was not reported as part of this research, as they are outside the scope, even though there may be shading or insulation impacts.

6.6 Case Study Analysis

Arising from a qualitative cross case study analysis of the reporting of various case studies (appendix 6) a number of key themes arose, which are addressed in hereafter:

1. Changing priorities in building retrofit
2. The impact of budget and time on the retrofit of college buildings
3. The use of scenario and risk analysis and its impact on goals and decision-making
4. Differences in energy conservation measures-light retrofit versus deep retrofit
5. Errors, Faults and repeated mistakes
6. A lack of post occupancy, measurement and validation
7. The lack of learning outcomes from iterative retrofits to the same typology
8. The role of the architect and engineer in the socio-technical process.

6.6.1 Changing priorities in building retrofit

As addressed previously (5.5), Irish building regulations (table 6.02) were prompted by the EU response to the Kyoto Protocol (1997) and EU Energy Performance Directive (2002). Incremental improvements, the introduction of incentives and the promise of feed in tariffs shifted client priorities from purely cost centric retrofit options towards energy performance in buildings over a period of 12 years, Waterford IT which had been the first of the RTCs to be built in 1970, was also one of the first to be renovated in 1995-2002 and subject to 1997 TGD L standards.

New Build' regulations for Energy conservation						
(Non -Dwellings)	Average Elemental U-Value in W/m^{2}K					
W/m^{2}K	**1976**	**1991**	**1997**	**2002**	**2005**	**2008**
Roofs	0.4	0.4	0.25	0.22	0.22	0.22
Walls	0.6	0.6	0.45	0.27	0.27	0.27
Ground Floors	0.6	0.6	0.45	0.25	0.25	0.25
Windows			3.3	2.2	2.2	2.2
Thermal Bridging			guidance	guidance	guidance	≤16%
Air Tightness			guidance	guidance	guidance	guidance

Retrofit' regulations for Energy conservation						
(Non -Dwellings)	Average Elemental U-Value in W/m^{2}K					
W/m^{2}K	**1976**	**1991**	**1997**	**2002**	**2005**	**2008**
Roofs	0.4	0.4	0.35	0.35	0.35	0.35
Walls	0.6	0.6	0.6	0.6	0.6	0.6
Ground Floors	0.6	0.6	0.45	none	none	none
Windows	0.6	0.6	3.3	2.2	2.2	2.2
Thermal Bridging			guidance	guidance	guidance	guidance
Air Tightness			guidance	guidance	guidance	guidance

Table 6.2 Evolution of Elemental standards in Technical Guidance Document L 1976-2008
(Ó 'Riain 2016)[544].

The building suffered from a lot of leaks especially on the southwest block, which was exposed to driving wind and rain. The buildings and estates manager at the time identified that "decision-making would have focused on the minimum requirements of the building regulations because capital funding was limited and we had a large building to improve" (McCauliffe 2015)[545]. Thermally broken double-glazed windows are fitted, externally aggregate panels were sealed (Fig 6.2) and cavity bead insulation was installed in 2002 resulting in a D2 energy rating (McAuliffe 2015), (Howley 2015)[546] and meeting retrofit energy regulations 1997. Low energy lighting and lighting improvements would not happen till much later.

Fig. 6.2 RTC Typology retrofit: Waterford 1998 mastic panel seals (Ó Riain 2015).

The revision of Part L 2002 resulted after the Letterkenny retrofit, in a significant improvement in 'new build' elemental U-values for the roof and more particularly for walls. The design team at Letterkenny elected to use Part L 1997 new build targets rather than retrofit targets for the renovation at Letterkenny (2002), thus changing the goal setting. Although no roof insulation is used (another floor is added instead) the external insulation brings wall U-values to 0.39 W/m^{2}k exceeding retrofit regulations by 33% and new build 1997 regulations by 13% (Delap & Waller 2002)[547]. Coady Architects adopted a 70mm external insulation adhered to the aggregate panel, with a 20mm ETICS self-pigmented render together with a low E double-glazing and no roof insulation resulting in a C1 energy rating (Daly 2015)[548].

Following Letterkenny, the renovation of the Carlow RTC typology in 2005, with Tristshler & Tristshler Architects, (who had previously refurbished Waterford RTC 2002), and Phelan Construction (O'Hara 2015)[549], saw the same upgrade of the external façade, with 70mm external insulation and an applied render, new double-glazed aluminium framed windows with no thermal break. The 2002 regulations were then in place and 0.39 W/m^{2}k would no longer meet 'new build' standards (0.39 W/m^{2}k walls) but would meet retrofit standards (0.6 W/m^{2}k walls). The Carlow retrofit was exclusively focused on improving the aesthetic of the building rather than the energy performance (Hassett 2015)[550].

The engineer's scenario and risk analysis of the 2005 planned retrofit of Dundalk IT recommended an external insulation to be the optimum energy solution to avoid interstitial condensation risk, with a potential saving of 42% on energy consumption. The FM Report (2005) recommended 112mm of external polyisocyanurate (PIR) insulation (Table 6.03); with an ETICS applied render system (U-Value: 0.25W/m^{2}K) thus meeting 2002 & 2005 Part L standards for new build. Combined with *Low-E* double-glazing, high and low ventilation openings (U-Value: 2 W/m^{2}K), air infiltration rate of 0.5 air changes/hr and energy efficient T8 lighting, TRVs, high efficiency boilers, the insulation of pipe work, resulted in a proposed C1 energy rating. The elemental wall standard would be 33% better than 'new build standards' for Part L 2005 and Part L 2008.

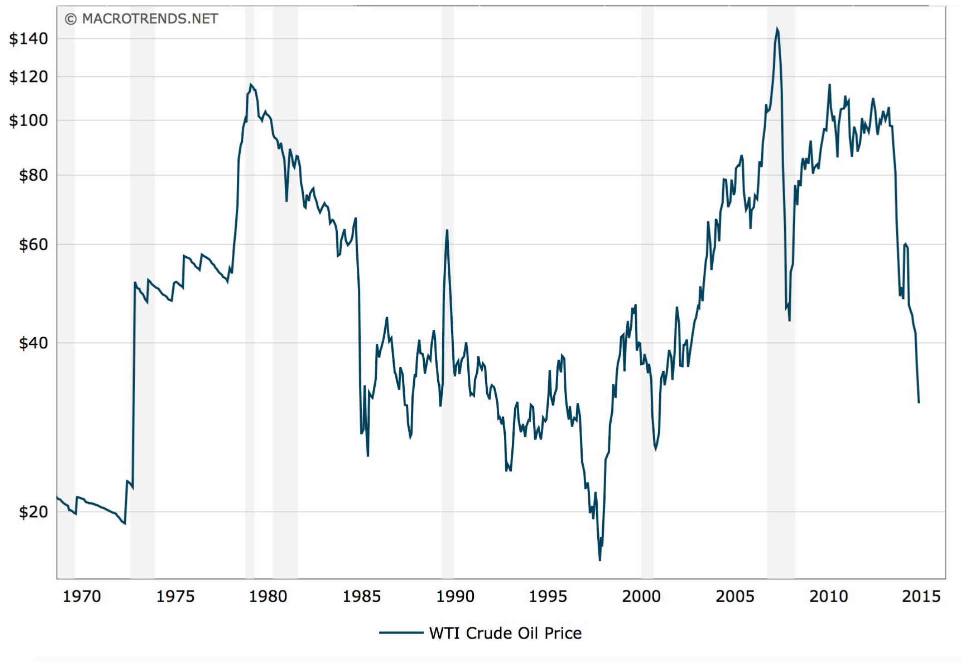
The refurbishment of Ó'Fiaich College in the summers of 2007/08 by Coady Architects, working with Semple McKillop Engineers, used the DKIT report and precedent at Letterkenny as a baseline for specification. The specification is directly comparable to the recommendations (Option 5 in table 6.3) of the 2005 Dundalk RTC feasibility report. There was only a marginal energy improvement between the 72mm and 112mm options, therefore the Coady architect went with a 80mm insulation thickness.

Results	Action	Thickness	Kwh/m^{2}a	% improvement	Condensation Risk
Baseline			2,108,679	2108679	2108679
Option 1	External Insulation	72mm	1,415,120	33%	none
Option 2	External Insulation	112mm	1,072,181	50%	none
Option 3	Cavity Insulation	100mm	1,457,727	31%	some
Option 4	Internal Insulation	71mm	1,401,989	33%	high
Option 5	External Insulation & TRVs	72mm	510,993	76%	none
Option 6	External Insulation & TRVs	112mm	467,515	78%	none

Table 6.3 RTC Typology: Performance analysis of Dundalk IT Retrofit energy conservation measures (Faber Maunsell 2005)

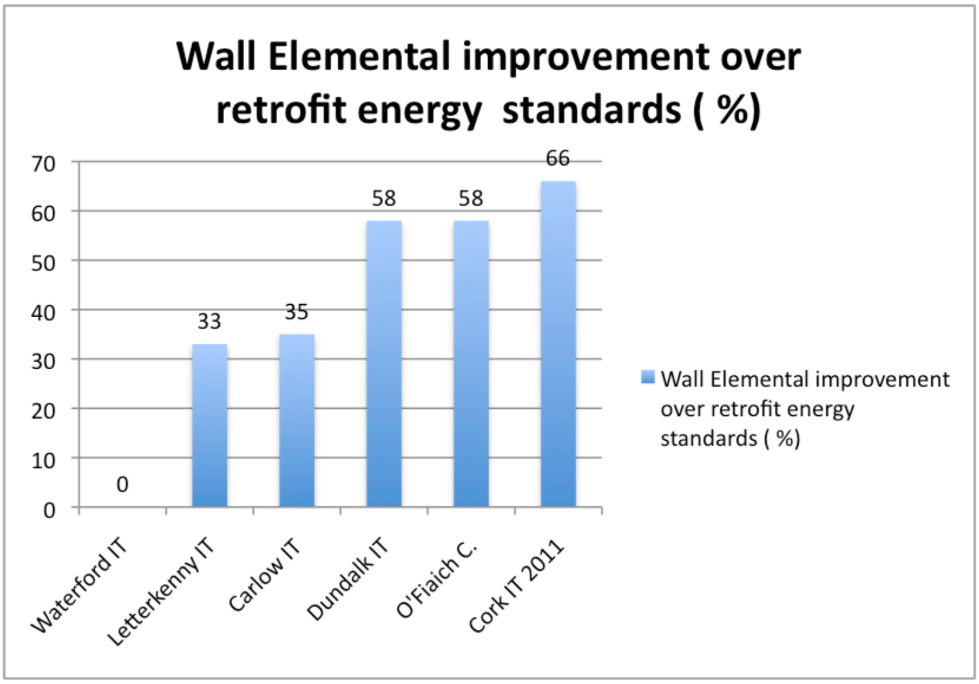
The ECMs included 80mm PIR insulation with an externally applied ETICS render system, double-glazed Low–E windows (2.0 W/m^{2}K), with high and low pivot windows, an air-tightness of 3.76 m^3 (hr/m^2) at 50 Pa, natural ventilation, TRVs and high efficiency fluorescent lighting (T8s), high efficiency condensing gas boiler and a PV array, resulting in a validated 54% saving in space-heating costs. The subsequent increase in building utility for night (236% increase in electrical night units) and weekend classes resulted in an 8% increase in electrical energy. The energy performance rating is a C1 and the specification is better than Part L 2008. The elemental wall standard would be 33% better than 'new build standards' for Part L 2005 and Part L 2008. Ó Fiaich College benefitted from SEAI and Department of education grant incentives for energy efficiency actions, which required post occupancy analysis.

Cork IT retained Coady Architects, working with ARUP engineers, in 2010/11, to propose a retrofit strategy master plan for 27,000 m^2 of its RTC 1974 blocks. The report proposed the same PIR external insulation with an ETICS cladding solution as Ó Fiaich College, with two optional insulation thicknesses (100mm and 170mm). The external cladding solution targeted a 33% improvement on 2008 TGD Part L 'new build' standards, with 100mm externally applied ETICS insulation system ($0.2W/m^2k$), roof insulation ($0.16W/m^2k$), double-glazed Low–E windows ($1.3\ W/m^2K$), with high and low pivot windows, an improved level of air tightness ($3m^3/m^2/h$) at 50 Pa, natural ventilation, TRVs and high efficiency fluorescent lighting (T8s). The project targeted a 30% improvement on new build standards. This project was never carried out because of funding difficulties, but it was followed by a pilot project, which developed independent targets.



Graph 6.2 Inflation Adjusted Oil Prices 1970 - 2015 (macrotrends.net)

Although building energy regulations for new build (rather than retrofit) improve elemental values once in the case study period, in 2002, maintaining the same performance values in 2005 and 2008 revisions, the new build standards together with grant incentives and rising oil prices (Graph 6.2) resulted in stepped improvements in energy goals set by the design team and the client at the outset of the project. In most cases the design teams used 'new build' standards as targets rather than the low policy intensity 'retrofit' standards. In 1998, when oil prices were very low retrofit priorities at Waterford became cost centric and focused on the minimum standards. In 2005, in Carlow, energy was also a low priority for investment decision-making, retrofit priorities at Carlow became aesthetic centric and focused on the retrofit standards rather than new build. The use of simulation analysis at Letterkenny and Dundalk were very useful in improving client goals over retrofit standards (Graph 6.3). A steady change in energy performance specification can be tracked by tracking elemental U-value improvements for walls (the most consistent ECM) over the case study period (Graph 6.3).



Graph 6.3 Wall Elemental improvements over retrofit energy standards (O'Riain 2016)

6.6.2 The impact of budget and time on the retrofit of college buildings

The second issue impacting the goal setting and strategy of the retrofits of the case study buildings were budget and time. A number of key themes arise both for this particular typology and their educational use. We found in chapter 5 that cost optimal analysis in Ireland (for public building retrofit) used a primary school as the reference building to represent a broad range of building uses. In the comparison of UK and Irish calculations, the research highlighted that the occupancy pattern and equipment densities of education buildings impact energy consumption[10]. The academic calendar of Institutes of Technology (formerly RTCs) and post Leaving Cert Colleges (O'Fiaich College) have resulted in low energy demand during large unoccupied summer periods. The academic calendar also results in two windows of opportunity for retrofits; the inter-semester breaks in winter (approx Dec 15th-February 1st) and summer (June 20th-September 15th).

[10] CIBSE TM46 (2008) benchmarks Primary school energy consumption at 190 kWh/m^{2}a, university buildings at 320kWh/m^{2}a and office buildings at 215 kWh/m^{2}a.

In all case studies from Waterford, Letterkenny, Carlow, and O'Fiaich College to CIT, retrofits were carried out in this period to avoid dislocating occupants in term. The impact of these shorter windows of opportunity impacts retrofit strategies. External works were preferred at many locations (Waterford, Carlow and CIT) to reduce internal churn[11]. The biannual retrofit windows also impacted external insulation technological solution. Unknown to Coady architects when specifying the ETICS render system, which would be adhered to the external insulation at Letterkenny, applied renders were suffering from post occupancy defects and failures. One of the key defects that impact the biannual retrofit windows is the propensity for render systems to delaminate due to phase change (freeze thaw) of trapped moisture between renders and insulation (fig 6.3). This risk factor saw all external render applications restricted to summer retrofit windows, resulting in staged retrofits at O'Fiaich College over the summers of 2007 and 2008.

Fig. 6.3 De-laminating render due to impact or freeze/thaw conditions (Ó Riain 2014).

[11] Churn" is the term used by facilities professionals to describe the continuous cycle of moves and changes within the workspace.

The limitation of time windows for retrofit to 11 weeks during the summer impacts the potential of energy conservation measures to achieve deep retrofits. Retrofits at Carlow and Waterford were effectively limited to façade works with minimal internal works. Air tightness measures could have more invasive impacts on perimeter internal wall mounted fixtures (radiators, electrical trunking, window sills, blinds and ceiling grids). Retrofit strategies for former RTC education buildings could therefore be restricted to façade oriented measures to address short refurbishment windows.

The Regional Technical Colleges became Institutes of Technology in the late 1990s, which gave them independence from Vocational Education Committees (VECs) allowing them to expand rapidly (McCauliffe 2015)[551]. This resulted in direct government funding (from the Higher Education Authority) to individual colleges in the form of recurrent capital grants, based on student populations. The core grants funds operational costs with Institutes dependant on summer works scheme grants to supplement core grant funding for building retrofits. Institutes of Technology unlike Irish Universities are unable to seek mortgages to fund building retrofits and are dependent on government funding or public private partnerships for new building.

Universities typically have a higher capital budget (€4000/m^2) than Institutes of Technology (€2400/m^2) (McCauliffe 2015)[552]. Therefore the budget for building retrofits in Institutes of Technology is dependent to a large extent on annual operational budgets. The Department of Finance have a 'Multi Criteria Analysis' for the assessment of public expenditure on capital projects under €20m and energy efficiency is not a criteria in the decision making matrix. Thus restrictive funding regimes can place client emphasis on lower capital cost strategies over longer-term energy efficient measures. This restriction would see the failure of Dundalk (2005) and Cork (2011) to secure funding to implement proposed schemes. The aspirations of project at Waterford (1998) were façade centric "because capital funding was limited and we had a large building to improve" (McCauliffe 2015)[553]. The capital allocation for the Cork (2011) retrofit was €1000m^2 whilst the EU estimated in 2012, that the 30-year lifetime investment capital replacement cost for NZEB performance building to be between €2397-€2756 (Table 7.12). Better energy performance goals were possible at O'Fiaich College largely because of the support of grants from the Department of Education and the Sustainable Energy Authority of Ireland (SEAI). Where client's goals are focus on capital budgets, better energy performance strategies can be limited. However, the analysis of the case studies showed that scenario analysis could play a key role in shifting client priorities toward improved energy performance goals.

6.6.3 The use of scenario and risk analysis and its impact on goals and decision-making

In two of the ten case studies, the engineer, identifying the most cost efficient combination of energy conservation measures to be applied, reported scenario analysis. Having simulated a baseline highlighting a thermal energy demand represented 70% of total demand mix, the engineers (Delap & Waller 2002) developed a simple excel based table identifying the impact of individual façade energy conservation measures (Table 6.4). The analysis projected percentage operational energy savings but did not quantify the cost implications of the capital investment or operational energy savings. The performance analysis helped the client choose an energy efficient strategy that exceeded minimum retrofit elemental standards for walls by 33% with no roof insulation (as they were extending up one floor). No risk analysis is carried out and external insulation is selected without any evidence of what informed this decision-making other than the projected U-value target.

Overall u-value

	Floor Area m^2	Roof Area m^2	Floor u-value W/m^2K	Roof u-value W/m^2K	Wall Area m^2	Window Area m^2	Overall Surface Area m^2	Wall u-value W/m^2K	Window u-value W/m^2K	Overall u-value W/m^2K	% improvement against base model	% improvement against Building Regs.
Base model	2455	2455	0.42	0.8	1,897	1,318	8,125	1.20	5.60	1.56	0%	-77%
Base model with Heating Controls	2455	2455	0.42	0.8	1,897	1,318	8,125	1.20	5.60	1.56	0%	-77%
Double Glazing Only	2455	2455	0.42	0.35	1,897	1,318	8,125	1.20	2.80	0.97	38%	-10%
Low E Glazing Only	2455	2455	0.42	0.35	1,897	1,318	8,125	1.20	2.04	0.84	46%	4%
External Cladding 70mm Only	2455	2455	0.42	0.35	1,897	1,318	8,125	0.39	5.60	1.23	21%	-40%
External Cladding 80mm Only	2455	2455	0.42	0.35	1,897	1,318	8,125	0.35	5.60	1.22	21%	-39%
External Cladding 70mm Insulation & Clear Float Double Glazing	2455	2455	0.42	0.35	1,897	1,318	8,125	0.39	2.80	0.78	50%	12%
External Cladding 80mm Insulation & Clear Float Double Glazing	2455	2455	0.42	0.35	1,897	1,318	8,125	0.35	2.80	0.77	51%	13%
External Cladding 70mm Insulation & Low E Double Glazing	2455	2455	0.42	0.35	1,897	1,318	8,125	0.39	2.04	0.65	58%	26%
External Cladding 80mm Insulation & Low E Double Glazing	2455	2455	0.42	0.35	1,897	1,318	8,125	0.35	2.04	0.65	59%	27%
External Cladding 70mm Insulation & Clear Float Double Glazing with Heating Control	2455	2455	0.42	0.35	1,897	1,318	8,125	0.39	2.80	0.78	50%	12%
External Cladding 80mm Insulation & Clear Float Double Glazing with Heating Control	2455	2455	0.42	0.35	1,897	1,318	8,125	0.35	2.80	0.77	51%	13%
External Cladding 70mm Insulation & Low E Double Glazing with Heating Control	2455	2455	0.42	0.35	1,897	1,318	8,125	0.39	2.04	0.65	58%	26%
External Cladding 80mm Insulation & Low E Double Glazing with Heating Control	2455	2455	0.42	0.35	1,897	1,318	8,125	0.35	2.04	0.65	59%	27%
Current Building Regulations	2455	2455	0.45	0.35	1,897	1,318	8,125	0.45	3.30	0.88	43%	0%

In the above table the window,wall and roof areas are modified to represent a building without the improvements which have already been carried out at LYIT, (i.e. the Phase1 Penthouse Extension and the Phase 2A Extension to the front of the ground and first floor). The 59% maximum improvement in the overall u-value is a 4% increase on the maximum overall u-value calculated for LYIT in Table 5 below.

Table 6.4 Cost-modelling for Letterkenny RTC 2002
(Delap & Waller Ltd 2002)[554].

The Dundalk Feasibility Study (2005) by Faber Maunsell (FM) and Coady Architects is important; as it is the first time we see both simulation analysis and risk analysis, but in the absence of cost analysis.

Results	Action	Thickness	Kwh/m^2a	% improvement	Condensation Risk
Baseline			2,108,679	2108679	2108679
Option 1	External Insulation	72mm	1,415,120	33%	none
Option 2	External Insulation	112mm	1,072,181	50%	none
Option 3	Cavity Insulation	100mm	1,457,727	31%	some
Option 4	Internal Insulation	71mm	1,401,989	33%	high
Option 5	External Insulation & TRVs	72mm	510,993	76%	none
Option 6	External Insulation & TRVs	112mm	467,515	78%	none

Table 6.5 RTC Typology: IT Dundalk Retrofit options
(Faber Maunsell 2005).

The engineers (Faber Maunsell) first modelled the energy demand baseline for each existing block (using IES Apache-Sim with windows closed) and the interstitial condensation profile using 'Dew Point' analysis. IES Apache Sim qualifies as a dynamic modelling software capturing linear heat transfer through the fabric using fixed U-values, it cannot capture an accurate figure for thermal bridging as a 10% reduction for thermal bridging can be applied to the constructions by default, but this is only used by UK Building Regulations (DSM method). It is not clear from the reporting if this happened. Dew point analysis will not capture the existing moisture content of the existing aggregate panel or the transient impact of weather conditions.

The analysis highlighted very different demand profiles for different blocks with the north block (1970 RTC Typology) having twice the demand profile to the south block (1976 different to RTC typology). The north block had lower occupancy patterns and a lower glazing ratio than the north block. An analysis of existing overheating and ventilation regimes, found that existing windows with 10° opening angles and "high occupant densities, classrooms, workshops and office areas in the south block struggle to reach the required fresh air requirement (CIBSE Guide A 2005)" (Faber Maunsell 2005)[555]. Arising from the existing baseline engineer had identified a low energy retrofit strategy prior to simulating options. An external insulation was preferred as it would address elemental heat loss, reduce thermal bridging and air infiltrations (to $10m^3/m^2/hr$ @ 50Pa). However architectural detailing insetting window locations created repeating linear thermal bridges (addressed in Ch.6.6.6).

The engineer then modeled six scenarios using a static sectional model with U-Value performance, interstitial condensation risk (using the Glaser Method for Dew Point Analysis)[556] and IES (Integrated Engineering Software) for dynamic simulation (again with the windows closed which are needed for ventilation). FM simulated external insulation at varying thicknesses, cavity insulation (cold bridging and condensation risk) and internal insulation (high condensation risk) (Table 6.5). The engineers recommend Option 6 with 115mm of external ETICS render, Air tightness ($10m^3/m^2/hr$ @ 50Pa), low emissivity double glazed windows (Low-E double glazed windows ($2.2W/m^2K$), TRVs and no roof insulation delivering up to 70% energy savings on modelling.

A risk to the scheme performance is the ECM integration. IES modelled energy performance where all windows are closed, in a building dependant on natural ventilation. Faber Maunsell (2005)[557] conceded this limitation in their report;“ if the windows were opened whilst the heating system was operational, the actual heating energy consumption would be greater than the values predicted due to increased heat loss”, therefore impacting the level of energy saving. Where TRVs are installed they would “increase heating energy consumption by compensating for any heat losses from open windows in order to maintain a constant room temperature” (Faber Maunsell 2005). Demonstrating 6 scenarios had helped the client develop a high-energy priority and set the project goals in line with EPD 2002 aspirations and future energy regulations; “the Institute intends to upgrade the façade to the standard that responds to the Energy Performance Directives which will be implemented throughout the EU” (Faber Maunsell 2005)[558].

Neither the 2002 Letterkenny, nor the 2005 Dundalk reports assess the future cost of energy, or include Net Present Value (NPV) calculations for building retrofit strategies, or its remaining lifespan. Dundalk’s (DKIT) retrofit was not implemented due to the lack of capital funding (Lait 2015). The findings of the report would go on to inform the subsequent Ó Fiaich College retrofit. The continuity of architects (Coady) from Letterkenny (2002), to Dundalk (2005), Ó Fiaich College (2007-08) and the subsequent Cork IT (2010) report, would see the same strategies being repeated at all of these projects, with some iterative performance improvements as legislation improved. However the lack of post occupancy analysis may have reduced learning outcomes normally associated with such continuity.

A 2014 DKIT report (Maas 2014)[559] on energy consumption evidences energy analysis, and an energy-centric priority amongst the client estates team. Despite the lack of retrofit action in 2005, the 2014 report establishes that the site-delivered energy consumption of DKIT (174kWh/m^{2}a in 2011) is 20% less than that of Cork IT (which was 208kWh/m^{2}a in 2011). This is largely because of renewable energy offset from wind turbine production.

Description (renovation type)	Final energy saving (% reduction)	Indicative saving (for modelling purposes)	Average total project cost (€/m^2)
Minor	0-30%	15%	60
Moderate	30-60%	45%	140
Deep	60-90%	75%	330
nZEB	90% +	95%	580

Table 6.6 Renovation type and cost estimates (BIPE 2011)[560]

6.6.4 Differences in energy conservation measures-light retrofit versus deep retrofit

Energy conservation measures can be broken down into three investment and intervention levels. Although the Energy Performance in Buildings Directive 2010 does not use the term 'deep retrofit' it does refer to "major renovations" (which can be defined on a member state level), which in an Irish case refers all renovations above 25% of the surface of the building envelope to all buildings over 250m^2 (Article 5, Energy Efficiency Directive 2012).[12] The 2012 energy efficiency directive, building on and supporting EPBD 2010, refers to 'deep renovation' with a significant percentage of cost effective energy reductions including staged retrofits. The BIPE (2011) categorized levels of retrofits as " minor, moderate, deep and nearly zero energy" (Table 6.6). Becchio (2013)[561] refers to 3 levels of energy retrofit; minor, moderate and deep retrofit. In table 6.07 ECMs are broken down into these three levels, on the basis of cost and level of physical intervention required. Minor retrofits are the low hanging fruit

[12] The floor area requirement has been shifted down from 1000m2 in 2010 to 250m2 by July 2015.

like lighting, TRVs and boiler upgrades, which are easy to carry out without significantly impacting occupancy or physical changes. These tend to be cost effective with faster payback periods than deep retrofit measures related to fabric (Ma et al 2012)[562], also generally referred to as 'technical retrofit measures' (Erhorn 2008)[563]. One moderate fabric related measure is selected, as it is also cost effective and relatively straightforward to carry out. Deep retrofit measures relate to more expensive building fabric and renewable systems[13]. Whilst window upgrades (deep retrofit) are the most consistent choice, lighting, TRV and boiler upgrades have been carried out in phases over time with the support of grants of incentives in many cases. An increasing shift towards deep retrofit measures is recorded from 2005 to 2012.

The first retrofit project at Waterford (1998) used interstitial cavity insulation together with mastic seals and decoration to the external aggregate panel joints. Although there was an increased risk of interstitial condensation as a result, there is no evidence of such issues 17 years later. The weather sealing of the existing façade was relatively successful in arresting the expansive spalling panel of panel fixings and panel delamination, which is a frequent occurrence at Cork IT. An improvement to lighting in all case study buildings was the most popular light retrofit measure with rolling upgrades to heating systems with TRVs. However, the addition of TRVs to an aging single circuit heating system may be compromised by system contaminants that may damage or impact TRV performance. The Dundalk report (2005) found that the addition of TRVs with external insulation would increase energy savings from 42% to 70% (with windows closed).

In cases at Waterford, Letterkenny, Carlow, Dundalk and Cork, all retrofit strategies avoided impacting internal services, making it difficult to achieve improved air tightness performances. At O'Fiaich College the combination of internal retrofit allowed for an air tightness of

[13] Kok, Miller & Morris (2012) establish cost effectiveness for energy savings measures (Kok, Miller & Morris (2012)

$3.6m^3/m^2/hr$ @ 50Pa to be achieved. Improvements to these standards are targeted ($3m^3/m^2/hr$ @ 50Pa) in the Cork 2011 proposal and $1.76m^3/m^2/hr$ @ 50Pa is achieved in the Phase 1 project (Zero2020 2012) at CIT (reported in chapter 7). The Phase 2 project at CIT in 2012 would see a return to a smaller range of energy conservation measures, similar to Carlow IT in 2005, because of cost centric goal setting by the client and a truncated design process, thus reversing the iterative improvements from 2005.

Retrofit Case Studies	Minor retrofit ECMs				Moderate Retrofit ECMs	Deep retrofit ECMs								
	Low energy Lighting/ sensors	TRVs	Boiler upgrade/ replaced	Internal Insulatio n	Cavity Insulation	External Insulation	Roof Insulation	Double Glazed Windows 2W/m2K	Triple Glazed Windows 1W/m2K	Thermal Bridging mitigation	Interstitial Condensation mitigation	Air tightness	Air Source Heat Pump	Site Renewable Energy-PV
Waterford IT		●			●			●						
Letterkenny IT	●					●		●						
Carlow IT						●		●						
Dundalk IT	●	●	●			●		●			●	●		●
O'Fiaich C.	●	●	●			●		●		●	●	●		●
Cork IT 2011	●	●	●			●		●		●	●	●		
Phase 1 CIT '12	●	●	●		●	●	●	●	●	●	●	●	●	●
Phase 2 CIT '12			●			●			●					

Table 6.7 RTC Retrofit case study energy conservation measures (O'Riain 2016).

6.6.5 Errors, Faults and repeated mistakes

Although sequential iterative improvements in performance standards were recorded over the timeline of the case studies, similar errors and problems were repeated. The RTC buildings are a similar typology located at 8 regional locations on a small island and as such each retrofit provides an exemplar to the subsequent project. Facilities managers at all RTC campuses meet on a regular basis sharing knowledge and projects and proposals at Letterkenny, Dundalk, O'Fiaich College and Cork IT (2011) had the same architects. Despite this level of continuity communication and relative proximity of precedents on one island, similar faults would arise in a number of case study buildings.

One defect that is common to Carlow and O'Fiaich College is that of render dis-colouration (fig 6.3). Johansson (2011)[564] reported the frequency and reasons for the "discolorations from growth of algae and moulds on the façades already a few years after construction" which up to then had been hard to explain. Johansson (2011) found that ETICS systems were more prone to Lichen and algae growth than traditional masonry constructions. The use of external insulation with an applied render reduces the heat capacity (thermal inertia) of the wall construction thus creating optimal conditions for algae growth, resulting in discoloration within a few years of construction. The cooler wall on the shelter north side of the building was found to be the most optimal location for discoloration. His findings are supported by hygrothermal analysis carried out by Barreira & Freitas in 2014[565] who found that algae growth was more pronounced in high humidity climates (decreasing the drying tome of a render) and on shaded facades (with low atmospheric radiation) where a low surface temperature results in higher surface condensation especially at night. Barreira & Freitas (2014) suggest that reducing the emissivity of the plaster would increase drying rates. Light colours like cream and white would have a higher emissivity than a black colour.

Fig. 6.03 Carlow IT (RTC) 2005 Discolouration associated with lichen growth is particularly severe on the leeward and colder side of the building (east) (Ó Riain 2014).

The continued specification of the ETICS renders system at Letterkenny (2002), Carlow (2005), O'Fiaich College (2007/08) and Cork IT (2010) and the failure to recognize discoloration and delamination issues highlights a number of issues. This might suggest that the lack of post-occupancy analysis by the design team resulted in the failure to recognize the defects, however the architect at O'Fiaich College was aware of the issue as it was discussed repeatedly with the client post completion (McGovern 2015)[566], yet the same solution was proposed at CIT by Coady Architects in 2011. The lack of precedent analysis by the design team prevented them from identifying discoloration issues at Carlow (2005) (Fig 6.03) when specifying the ETICS system for O'Fiaich College (2007/08). The pilot project in Cork in 2012 did not use the ETICS render system because of risk and precedent analysis by the research team.

Fig. 6.4 Ó'Fiaich College. Lichen growth on north façade of External Thermal Insulation Composite Systems (ETICS) renders.

The north elevation is sheltered from the sun, resulting in an uneven discolouration of the render where moisture condenses on the textured surface. The uneven or stratified nature of the growth may be attributable to colder surfaces at higher points (Ó'Riain 2015).

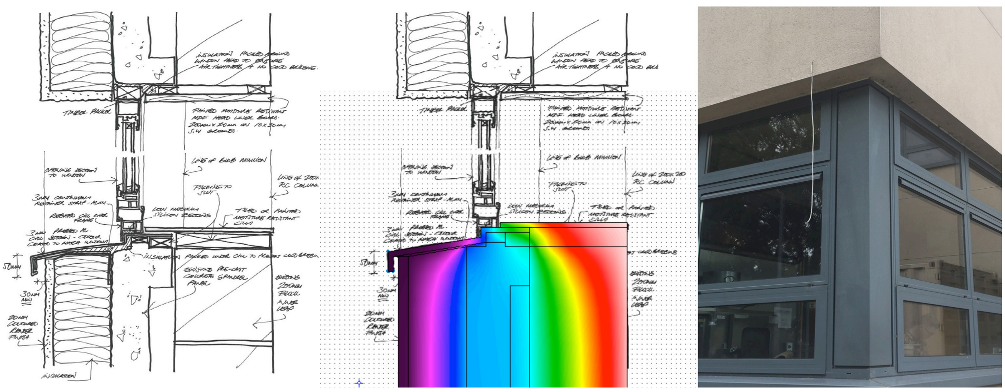


Fig. 6.5 Ó'Fiaich College sketch section (left by Coady Architects), Therm 5 visualisation of heat flow (Centre by Ó'Riain 2013) and Ó'Fiaich College corner window (Ó'Riain 2015)

The repeated specification of render systems would not be the only fault. The repetition of recessed window positions would have created linear thermal bridges at Waterford (1998), Letterkenny (2002), Dundalk (2005) (2007-08) (Fig 6.5). In all of the aforementioned case studies the window location is supported from the existing external cladding rather than being located in line with the insulation. This created weak points along the sill and head of windows where low (winter) surface temperatures could create repeating linear thermal bridges, creating condensation risk and mould growth. In case 6.06, water appears to be penetrating the windowsill on the sheltered easterly courtyard façade of O'Fiaich College. The presence of a cellulose material the window board, and low surface temperatures result in fungal growth, and material decay. This also potentially signals the existence of more concealed cavity condensation.

Fig. 6.6 Ó'Fiaich College water ingress, low surface temperatures, a cellulose material and mould growth (Ó'Riain 2015)

Sketches in the Coady proposal for Cork in 2011 evidence a change in detailing from O'Fiaich College. Windows were proposed to be contiguous with insulation, passing in front of structure, thus mitigating thermal bridging issues. This was not modelled or simulated. In the 2012 pilot project (Phase 1-reported in the next chapter) the research team identified this issue from risk and precedent analysis, informing design strategy, and carried out thermal bridging analysis to validate detailing.

Faults and errors on the façade retrofit at Carlow demonstrate the impact of an aesthetic centric approach. Recessed window positions created linear perimeter thermal bridges aggravated by pressed aluminum sills, with poor and often unsealed junctions between insulation and existing fabric (allowing water ingress to cavity).
Linear thermal bridging at the ground/foundation level, building corners and un-insulated first floor underpasses (Fig. 6.07) highlight critical and substantial risks to conductive scheme heat loss. Indeed, the thermal bridging detailing would not comply with concurrent new build regulations in 2005 for sill, jamb lintel and junction details (Department of Environment 2005)[567].

Fig. 6.7. Carlow RTC site inspection Nov 2010. Evidence of insulation gaps. Right-left: 1. Window junctions sill wall 2. Link underpass 3. Building corner spandrel 4. Repeating thermal bridge connection (Ó'Riain 2014).

The separate application of shading devices in 2010/11 does not involve the same architectural practice. Fixings penetrate the new insulation layer, fixing into the external aggregate panel at two points on horizontal slabs, every 2.4m, creating repeat point thermal bridges, and repeating interlayer hygrothermal penetration. This raises the risk of aggravated expansive spalling to the existing panel at new fixings. The continuity of architects from Waterford (2002) to Carlow (2005) shows some learning outcomes, but a lack of client priority for energy-centric decision-making.

The interdependence of ECMs in energy centric retrofits is very important in delivering validated energy savings and adequate interior environmental conditions. However low intensity retrofit regulations do not mandate designers to measure risks, simulate performance, minimize energy loss, or validate design stage results. Thus clients are free to set goals for design team actions, which can undermine energy performance and environmental conditions by taking a façade led approach as demonstrated in Carlow and later in Cork's Phase 2 (2012) project, which is reported in the next chapter.

6.6.6 A lack of post occupancy, measurement and validation

The validation of energy retrofit performance was absent in all case studies for many years, except for O'Fiaich College, where post occupancy performance reporting (2012) was a requirement of the Department of Education energy unit. The level of post occupancy performance analysis by client teams was entirely subjective. The estates manager at Carlow reported the 2005 retrofit to be "a definitely warmer building and looks much nicer too", whilst most estate managers would have been aware of the improved energy performance ratings (unfortunately DEC energy performance ratings are campus ratings rather than building specific). The lack of sub metering at many locations prevents client teams from easily interrogating post occupancy performance and carrying out energy audits. None of the case studies demonstrated a post occupancy element to the design team process. Energy auditing at Cork in 2010 (Purcell 2010), O'Fiaich College (2012) and Dundalk (2014) give the most in-depth analysis of building specific energy demand. The Socio-Technical design process weakness in post occupancy analysis may undermine prevent learning outcomes, retard iterative improvements from project to project; undermine capital investment strategies and client awareness of operational energy issues.

Way & Bordass 2005 (2011)[568] highlight that most clients feel like crash test dummies, abandoned after the completion of the building by the design team when they need support the most. This can lead to tensions and frustrations between the client and the design team. As improved energy regulations place pressure for 'greater predictability' to performance outcomes, thus energy audits and post occupancy performance evaluation becomes more important. Display energy Certificates, which measure all post occupancy energy demand from billing include both regulated (the focus of the design team) and unregulated energy loads (plug loads which are normally outside the remit of the design team). Therefore a client confidence in low energy retrofit strategies can be undermined by poor post occupancy DEC ratings. The O'Fiaich College audit (2012) highlighted the increased level of electrical energy consumption post occupancy through increased building use.

The general lack of post occupancy evaluation in the socio-technical design process is common in the design and build paradigm, but is increasingly important for validating design stage performance in an EPBD (2010) context, both to confirm that goals have been achieved and to inform future projects through cyclical learning outcomes.

6.6.7 The lack of learning outcomes from iterative retrofits to the same typology

The lack of post occupancy analysis by both the design teams and the client teams impacts learning outcomes. In 6.6.5, architects fail recognise faults that are repeated in subsequent design proposals. Thermal bridge simulation and detailing, the risk of interstitial condensation, lichen growth on ETICS renders and the lack of cost analysis are all features that repeated across case studies.

A variety of post occupancy energy performances are recorded at all case study buildings through Display Energy Rating Certificates (DECs).

DECs are required for all public buildings, measuring a building's post-occupancy energy consumption from billed energy (rather than its design elemental values, active service packages and renewable contribution, as the Building Energy Rating (BER) certificate does). A DEC records all energy consumption from billed energy including non-statutory (plug) loads. The socio technical design process for low energy retrofit biases towards the reduction of space heating loads because of EU Directive demarcations and national regulations. This can lead to actual and perceived performance differences between simulated energy performance (excluding plug loads) and billed post-occupancy energy consumption in buildings (including plug loads). This can lead to a perception issue, which, as Blomsterberg and Engvall (2011) noted can be difficult to overcome and may undermine confidence in low energy retrofit strategies.

The low level of post occupancy regime by client and design teams is reducing learning opportunities from such faults, and thus impacting iterative design improvements from project to project. As an example of this a client representative of at CIT (Cork) Phase 2 RTC retrofit (2012) was asked whether there any issues post occupancy with interior air quality or overheating? The client representative answered "No, not that I am aware of" (Brennan 2015)[569]. Way & Bordass (2005) noted "conventional [design] services usually stop at 'practical completion' apart from dealing with defects. Clients therefore are more involved with post occupancy issue and faults. Clients and users may also suffer from a lack of training during the hand over period (Way & Bordass 2005)[570] and may not know how to or be capable of operating or controlling their environment.

Way & Bordass (2006) argued that in most socio-technical design processes there were a tendency to 'fit and forget', where there was little design team responsibility in client training or post occupancy evaluation (POE). This is particularly problematic in low energy retrofits where there is an inter-dependence of ECM performance and reliance on Building Monitoring Systems.

Hadjri & Crozier 2009[571] argues that the existing socio-technical design process in the UK is truncated at practical completion where Zeisel (1984)[572] insisted that the design process needed to be cyclical. Although "most designers and contractors have traditionally shown little interest in learning from how their buildings actually perform in use; and most clients have certainly not wanted to pay them to do so" (Way & Bordass, 2005)[573]. Therefore, there is a POE service gap in the socio-technical scope of services for building retrofit. Such additional services need to be integrated into a process map and additional services paid for by the client. Way & Bordass (2005) proposed an augmentation to the design process called 'Soft Landings'[14] for POE. Way's (2006) paper quantifies the cost of POE calculating that the additional service cost (€12k for 16+ schedules visits over a 3 year period) would represent a relatively minor cost in the context of a €15m-€20m build (Way, 2006)[574]. The service cost in retrofit may be more onerous however as a POE percentage of the overall retrofit budget would be much higher. Although PROBE studies had highlighted performance gaps arising post occupancy, there remains major barriers to its adoption in practice. Cooper (2001), (Jaunzens, 1999) and (Zimmerman & Martin, 2001) identified a number of barriers to POE adoption, including who pays for the service, what the benefits are and who shoulders the blame for the findings. The BRE set out a three-stage process for post occupancy evaluation with a 3-6-month operational review, a 12-18-month Functional Performance Review and a three-year strategic review (McMillan, 2015)[575].

Menezes (2012) however argues that POE is a critical augmentation to the design process in order to overcome gaps between predicted and

[14] Soft landings is BSRIA(Building Services Research and Information Association)-led process designed to augment the design process with post occupancy evaluation.

actual energy performance in non-domestic buildings (Menezes et al., 2012)[576]. Without structured post occupancy evaluation, energy or environmental performances are unlikely to be captured and goal setting addressed.

The low level of case study post occupancy analysis and a poor level of precedent analysis by design and client teams create process breakdowns, which result in a failure to inform the design processes and design iterations. Visual inspections and stakeholder interviews could inform iterative improvements and avoid repeating mistakes across large building volumes.

6.6.8 The role of the architect and engineer in the socio-technical design process.

In all case study design processes, the engineers were responsible for energy simulation, reporting, and validation. Despite the selection of ECM strategies at a macro level by engineers, architectural detailing at Dundalk and O'Fiaich Colleges did not assess the impact of thermal bridges which would potentially undermine design stage simulated performances and a greater level of post occupancy energy losses. The lack of capital cost analysis in the scenario analysis at Letterkenny and Dundalk limits client decision-making and potentially undermines the financial viability of the project. The modelling of retrofit energy performance with the windows closed using IES simulation software by the engineer, with a natural ventilation strategy in combination with Thermostatic Radiator Valves (TRVs) potentially overestimates operational energy savings further undermining the financial case for energy retrofit. In section 6.6.3 we addressed the use of IES by the engineer (which depends on a uniform 10% setback for thermal bridging) and the lack of thermal bridging analysis by various architects on all case studies highlights both process and knowledge gaps that can impact retrofit performance.

The demarcation of responsibilities within the existing socio technical design process does not address the need for an appreciation, knowledge and understanding of the interdependence of ECMs to building energy performance. In this regard case studies highlight an emerging demarcation gap. Engineers are responsible for the simulation of energy performance but not for validating the performance of architectural envelope detailing. Conflicts arising from the lack of Building Performance Simulation (BPS) tools by architects are unlikely to be resolved over night as the survey of professionals in Ireland highlighted a very low adoption of BPS tools. Whilst there is now ubiquitous training of BPS tools at undergraduate level for architectural technologists in Ireland, only one course was found to have simulation software training for undergraduate architects (University of Limerick). Graduate architectural technologists may address the skills deficit in practice in time, however external specialists or facilitators may be needed in the short term to address the immediate shortfall in skills.

The goal setting by the clients was critical to the design stage response by the design team as a whole. Without improved goals or targets the design teams could not select better energy conservation measures because of cost restrictions. Therefore, the pre-design process is critical in driving design stage decision-making

Whilst exemplar reporting is demonstrated in the Dundalk proposal (2005) the lack of cost analysis and the use of 'Dew Point' assessments undermine the value of the report's findings for investment decision-making and risk assessment. However, the Dundalk report remains the most rigorous of the reports in structure and approach. The Cork 2011 proposal budgeted only one option (112mm external insulation), and did not carry out scenario analysis unlike the Dundalk (2005) or Letterkenny (2002) reports.

6.6.9 Findings

Pre-design process issues include: The above issues contribute to policy, investment decision-making, design-process and technical barriers to achieving low energy efficiency and nZEB buildings in Ireland. These issues are thematically condensed and compared to existing barriers/ gaps published by Golove (1996) and Steinmüller (2008) to illustrate a broadening of knowledge in Table 6.9 & 6.10 on the following page.

Deep Retrofit Barriers
Socio Technical Process

Stage	Barriers
Pre-Design Stage Barriers	**Pre-Design Stage Barriers**
	Low intensity Retrofit regulations disincentive deep retrofit client goals.
	A poor level of access to capital finance and finance models (ESCOs) undermine long term investment.
	The use of simple payback methods for retrofit based on operational cost savings undervalues the benefits of added capital value, extended lifespan and environmental improvements, thus biasing decision making toward shallow retrofit strategies.
	A falling level of incentives and the lack of tax breaks for longer term for deep retrofit undermine investment models.
	The lack of scenario analysis by clients and design teams undermine informed strategic decision-making for deep retrofit, extending the design process.
Design Stage Barriers	**Design Stage Barriers**
	There is a low level of Building Performance Simulation (BPS) analysis for architectural detailing.
	A poor level of appropriate precedent research was carried out at case study buildings.
	The lack of BPS use for risk analysis for thermal bridging and interstitial condensation.
	The lack of post occupancy analysis leading to repeating specification problems (delaminating render, discoloration of render, thermal bridges, mould growth).
Post Occupancy Stage Barriers	**Post Occupancy Stage Barriers**
	There is a lack of performance validation and post occupancy analysis by design teams and clients.
	A lack of sub metering is a barrier to accurate energy auditing.
	A lack of staged commissioning can impact building energy performance.
	Increased post occupancy plug loads increased electrical energy in the overall energy demand mix.
	Increased utility of the building can often lead to higher energy demand.

Table 6.9 Deep Retrofit Barriers arising from case study projects (Ó'Riain 2016).

Deep Retrofit Barriers
Practice

Architectural Design Process nZEB barriers
The lack of BPS simulation analysis for architectural detailing.
A poor level of appropriate precedent research was carried out at case study buildings.
The lack of BPS use for risk analysis for thermal bridging and interstitial condensation.
The lack of post occupancy analysis leading to repeating specification problems (delaminating render, discoloration of render, thermal bridges, mould growth).
A lack of learning cycles impacts knowledge and understanding.

Engineering Design Process nZEB barriers
Dependence on simulated existing energy performance can undervalue operational energy demand.
Simulation analysis using 'closed window' modeling, understating energy demand.
Engineers did not simulate risk analysis for thermal bridging and interstitial condensation in architectural details.
Cost analysis and net present value was not employed as part of scenario analysis, which can limit client decision-making.
The use of 'Glazer Dew Point' analysis (rather than WuFi Analysis) limits risk analysis in retrofit contexts.
There was a general lack of post occupancy analysis and performance validation of case study buildings.
The use of TRVs with opening windows acting as natural ventilation could increase space heat demand.
The use of TRVs with a deteriorating circulation system could impact the lifetime of the valves.

Table 6.10 Discipline specific barriers to better energy

The issues highlighted in tables 6.9 and 6.10 highlight issues arising directly from cross case study comparative analysis. Many issues are related to the input of various key stakeholders with the client having the greatest impact on goal setting (Table 6.9) at the pre-design stage (Table 6.8), thus impacting decision-making and the selection of energy conservation measures at the design stage (Table 6.10). Disciplinary process issues also compromise the potential for better energy performance (Table 6.10). The 'Socio-technical process for nZEB retrofit is therefore open to a variety of issues that shape the realised retrofitted artefact, including policy, investment decision-making, design-process and technical barriers to achieving nZEB performance in Ireland. In chapter 1, the research introduced existing literature that established barriers to nZEB retrofit in a global context. In figure 6.08, the barriers to nZEB retrofit in Ireland (arising from case study analysis) are thematically condensed and compared to existing barriers/ gaps published by Golove (1996) and Steinmüller
(2008). This establishes new knowledge in an Irish economic, legislative and design practice context, thus broadening the understanding of systemic barriers to nZEB retrofit, and allowing for the development of a an outline socio technical process map to address nZEB retrofit performance in an Irish context (Figure 6.8).

6.7 Synthesising an outline energy centric retrofit process map from case study analysis

An 'outline' socio technical process map (Figure 6.9) has been synthesised from exemplar case studies and highlighted process gaps (tables 6.8. 6.9 & 6.10). The pre-design stage reporting of Dundalk (2005) together with the design and post occupancy validation stages of O'Fiaich College were mapped (2006-07) identifying aspects of the processes that could be augmented to improve energy conservation outcomes (Table.6.9). The map is divided into three key phases, reflecting pre-design, design stage and post-occupancy/validation. The final stage is reviewed informing improvements to the process, solutions and artefact for subsequent projects creating a cyclical design process (Zeisel 1984)[577].

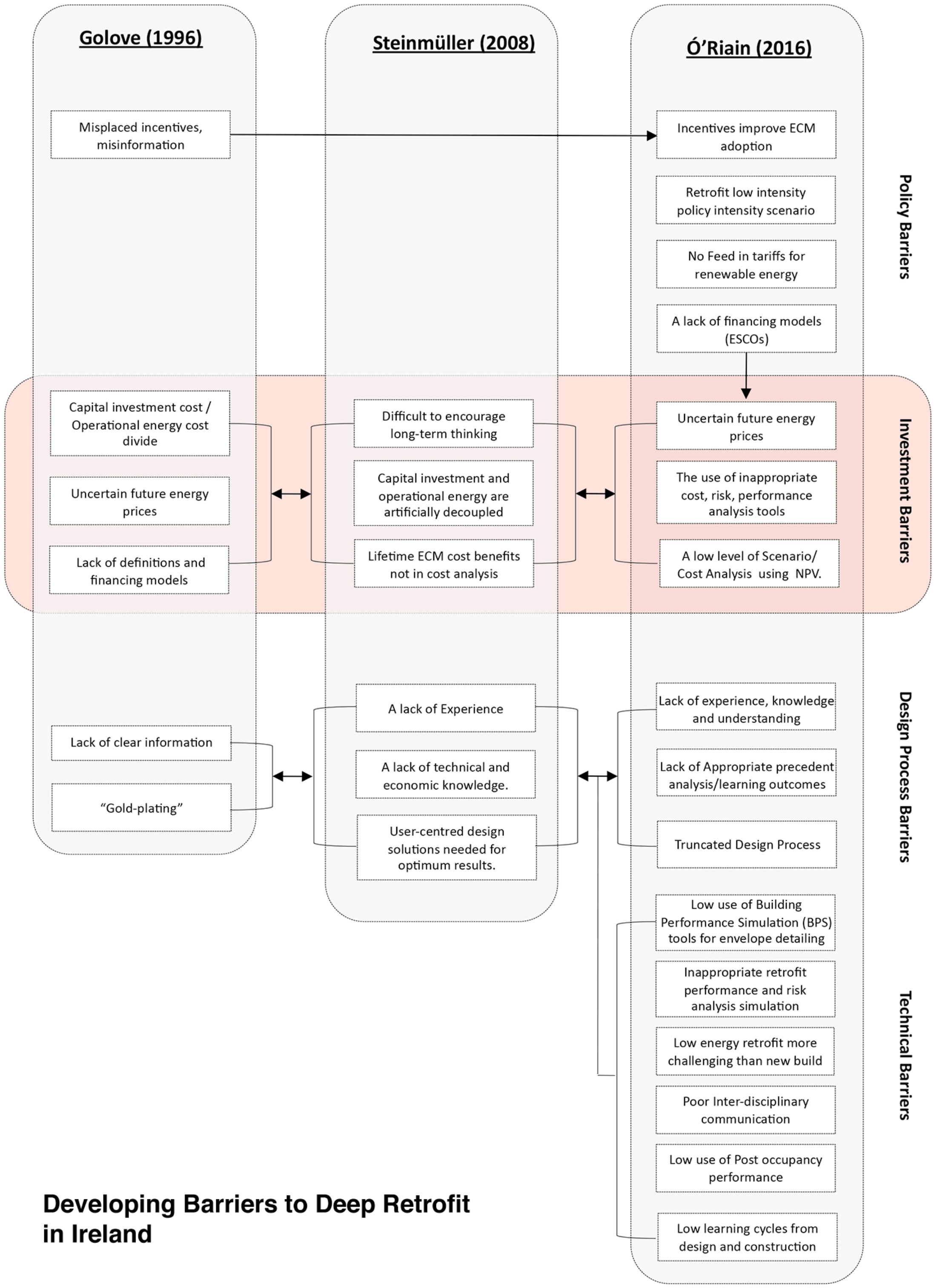


Fig. 6.8 Expanding on existing barriers to Deep Retrofit in Ireland. (Ó'Riain 2016)

Stage 1 of the process, the pre-design stage, is bounded by a funding approval for retrofit, which can prevent the project from moving forward. Therefore, process actions that are required to develop a retrofit strategy are included in this stage.

Stage 2 of the process, the design & construction stage, is bounded by existing practices processes, but requiring augmentation with building performance simulation tools by the design team or external specialists/facilitators in the short term and by graduate architectural technologists in the medium term. Architectural teams in case studies did not use BPS tools, however they are required to minimise risks and validate architectural detailing. This could potentially be an external resource to the existing design process. Energy performance contracting is included as a methodology for funding upgrades through ESCOs, where capital funding is financed through operational energy savings (Scott 2004)[578] to address capital investment barriers in Institutes of Technology (former RTCs). In energy performance contracting (EPC) the ESCO brings an EPC Facilitator to the construction stage to ensure the correct "implementation of agreed energy conservation measures".

Stage 3 of the process, the post occupancy stage, is bounded by practical completion of the construction stage. Adopting the three BRE Post occupancy stages:

3-6-month operational review

12-18-month Functional Performance Review

3-year strategic review

(McMillan, 2015)[579]

This is augmented with commissioning, client training, post occupancy air tightness testing, energy auditing and final reporting feeding back as learning outcomes for future strategic retrofit strategies and improvements to the existing building.

6.8 Conclusion

Design team decision-making is impacted by a wide array of internal and external factors. The case studies highlight shifting client priorities towards better energy performance exceeding minimum building energy standards in a low policy intensity context. The most critical factor influencing design stage decision-making was pre-design stage goal setting. This would be informed though the availability of capital for investment in the project, new building energy standards and scenario analysis, adopted in some cases. Energy centric goal setting resulted in higher stepped improvements from precedents projects where scenario analysis was employed. This often involved the simulation of energy performance and risk analysis by engineers, but never by architects. A failure to validate architectural detailing energy implications highlighted the lack of BPS use by architects and process gaps that could lead to post occupancy energy performance gaps. The lack of POE demonstrated a ‘fit and forget’ policy truncating the design process at practical completion stage.

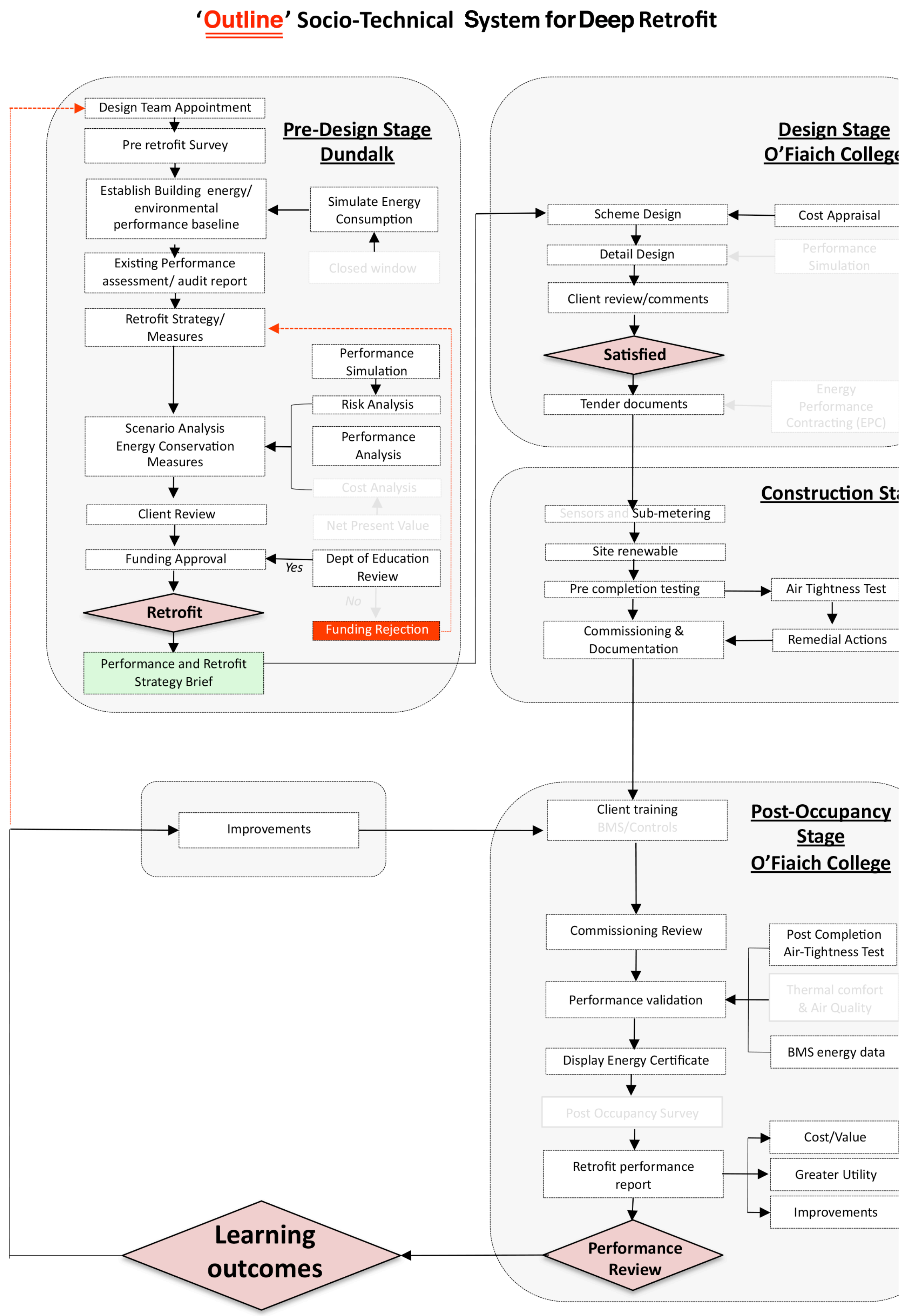


Fig. 6.9 'Outline' Socio Technical System for Deep Retrofit (Ó'Riain 2016)

The process barriers to low energy retrofit in Ireland are synthesised in figure 6.12. They broaden and deepen the knowledge of what is a complex systematic challenge with a wide degree of inter-related variables, allowing an understanding of key issues in various parts of the 'wicked problem' (Churchman 1967)[580].

From this understanding, we are better positioned to postulate improvements to the existing socio technical system, building on case experience. The 'outline' socio technical system, which has been developed from the case studies and process barriers, will be compared to existing literature and pilot projects in the following chapter for validation or amendment. The process will then be tested in a pilot project, where the performance outcomes will be measured and the interactions of the key participants to establish the potential of such an augmented socio-technical design process to meet nZEB performance. A 'standard case' project will also be studied without an augmented socio-technical design process.

CHAPTER 7

TESTING SOCIO-TECHNICAL PROCESSES FOR ZERO ENERGY RETROFIT THROUGH AN APPLIED PILOT PROJECT

Chapter 7: Testing Socio-Technical processes for zero energy retrofit through an applied pilot project

7.1 Introduction

Based on findings from case study analysis, tacit knowledge, and a review of related literature, this chapter sets out to test and refine the socio technical design process for deep retrofit through applied pilot projects. A review of existing literature on performance oriented design processes informs a theoretical mapping of an optimum "Socio-Technical System for NZEB Retrofits". Case study analysis will compare a pilot nZEB retrofit project (Phase 1: the deviant case, Silverman 1993[581]) augmented by an expert team of researchers, to a control retrofit project (Phase 2-the standard run case) to validate or amend the "Socio-Technical System for NZEB Retrofits". A synopsis of Phase 1 with measured and validated energy and environmental performance quantitative is reported in this text and in greater detail in Appendix 7.

A qualitative analysis[15] of 2278 coded stakeholder interactions from communications, reports and design team minutes adopted mixed methods data analysis to examine decision-making in the design process and its consequences. Iterative refinement of codes into categories limited by specific criteria, and then themes that characterise conflicts or processes in the socio-technical construct of the retrofit cases studies, provide a basis for visually mapping the content, interactions and problems. The mapping allows for frequency analysis of the database, thus highlighting critical steps in systematic mapping of an nZEB design process in Ireland. The comparison of deviant and standard run cases demonstrated the truncated nature of the existing socio-technical design process, in the context of RTC retrofits, prompting a discussion on findings in Chapter 8.

7.2 A synopsis of the research and systemic barriers to NZEB retrofit

The design and construction of the Regional Technical Colleges from

[15] The methodologies and methods enployed in this chapter are covered extensively in Chapter 2.

1968-1974 was compromised by budget, knowledge, an understanding of the impact of envelope heat loss on operational energy, and experience with the design and construction of system building. Having exceeded their functional lifespan these concrete structures are well suited to either replacement or upgrading through performance oriented retrofit extending their lifespan for a further 40 years. Through retrofit, the embodied energy of the existing structure can be reinvested, with envelope and active systems being replaced to improve the operational energy performance of the buildings.

Passive strategies including super-insulation, good air tightness and maintaining controlled ventilation have been demonstrated as key energy conservation measures (ECMs) to be employed, before addressing remaining energy demand with active systems that may have shorter lifespan. Since the first oil crisis prompted a greater awareness of energy efficiency in buildings a variety of systemic barriers have retarded the development of low energy buildings. A low intensity regulatory environment and the poor availability of financing models have undermined the development of the low energy-building sector in Ireland. Without this external framework, market forces result in lower performance targets for RTC case study buildings at the outset of retrofit project, truncating design processes, impacting decision-making and reducing opportunities for the adoption of energy conservation measures.

In Ireland, the absence of mandatory minimum energy standards and a falling level of incentives for building retrofit undermines investment priorities and performance aspirations in low energy building retrofits. Existing low mandatory standards undermine client or developer confidence in, and demand for the EPBD 2010 NZEB standards. Ireland's high policy intensity scenario (HPI) for the energy performance of residential buildings (introduced in 2011) has resulted in "94% of properties built in last 6 years awarded A or B [energy performance] rating…[compared to] 36% of dwellings constructed during 2005-2009" (Central Statistics Office, 2016)[582]. That indicates that the new built population increased by a quantum of 58%, representing almost a trebling of market penetration principally through improved regulations.

Cost optimal calculations to update Irish building energy standards for the retrofit of non-residential buildings in 2017 set a "moderate technical intensity scenario" (Wesselink et al., 2010)[583] where building envelope upgrades are not required for retrofit, in favour of shorter lifespan low energy active system upgrades. These will adversely impact market demand for nZEB retrofit in Ireland and client goals at the outset of retrofit projects. "If performance levels in building codes and retrofits remain far from their state-of-the-art levels, accelerating building retrofits will not bring major climate benefits" (Urge-Vorsatz 2014)[584] and Ireland will not meet the aspirations of the nZEB retrofit embodied in the Energy Performance Directive. Lawson (1980)[585] underlined the important role of legislation in design team decision-making, "planning authorities can provide a brake to restrict the clients commercial drive".

Although voluntary rating tools for sustainable buildings, such as BREEAM Excellent, LEED Platinum, and a 6-Star Green Star, are important in improving market demand for low energy buildings. However, Reed, Bilos & Wilkinson (2009)[586] warned that "in an era of international property investment where it is possible to directly compare values of individual buildings in different countries with a view to potential acquisition, unfortunately rating tools do not exhibit the same level of comparability due to their unique characteristics and focus. This in turn may hinder the take-up rate of sustainable rating tools and also be a barrier to increasing the knowledge about sustainability and buildings."

Building on Golove's (1996) barriers to NZEB adoption and Steinmuller

(2008) knowledge gaps retarding the wider diffusion of NZEB policy, a number of regionally specific barriers to NZEB retrofit have emerged in the process of the research (Fig 7.4) at the end of the previous chapter). A review of existing research, case studies of RTC retrofits and a survey of Irish design practitioner's highlights problems that exist in the socio-technical system (STS) of performance oriented design processes in Ireland.

The predominant use of simplified economic payback assessments of ECMs in RTC case studies, a lack of Irish financing models (ESCOs) and the demonstrated absence of the use of Net Present Value (NPV) in assessing RTC building retrofit measures all undermine client's goals and targets for performance oriented retrofits.

Findings from a survey of Irish design practices (Chapter 5) illustrates that the socio-technical design process in Ireland may suffer from a low usage of energy auditing, economic scenario analysis, performance assessments, risk assessment, building performance simulation modelling, performance measurement/validation and post occupancy evaluation due principally to cost, time, software and training issues. A low use of building performance tools amongst Irish Architects (26%) could be resulting in the lack of confidence felt by Architectural practices to deliver NZEB retrofit performance (only 40% of architects felt they could achieve a measured NZEB retrofit performance). This implies that socio-technical issues may be prevalent beyond RTC retrofits, in the wider Irish design process for building retrofits. The low use of building performance simulation (BPS) tools by Architects in Ireland may limit innovative project specific thermal bridging detailing and the general knowledge informing risk analysis. The lack of use of hygroscopic transfer simulation tools amongst architects, especially in the context of external insulation strategies in retrofit, creates potentially unforeseen project and building performance risks. The lack of post occupancy evaluation (POE)/performance validation in the case studies resulted in the repetition of problems from project to project (thermal bridging detailing and lichen growth on applied renders). The 'routinization' (Brown, J.S. & Duguid, P., 2000)[587] of the socio technical system for the design of buildings in Ireland may be leading to "a dependence on common assumptions" (Burton 1979)[588], a reliance on accumulated experience, rules of thumb (Lam, Wong & Henry, 1999)[589], use of elemental backstop values and *Acceptable Construction Details* (ACDs) could be truncating the design process in Ireland and limiting its ability to deliver measured nZEB performance through retrofit. Brown & Vergragt (2008)[590] argues that such socio-technical systems are slow to change their professional norms and practices.

The research thus far has illustrated that there is "scale and complexity" (Brown & Vergragt 2008) to the problem faced by the socio-technical system, challenged with achieving NZEB retrofit performance in Ireland. Both external systemic legislative and economic issues undermine demand and therefore experience of low energy retrofit in Ireland. Therefore, the socio technical design process can be truncated to respond to a narrower and less inspirational set of performance goals.

Regionally specific Irish barriers to NZEB or nZEB retrofit have arisen through this research (specifically in chapters 5 and 6) which include:

1) **A low intensity policy scenario:** The absence of minimum NZEB level building standards, and poor mandatory energy performance standards represents an existing low policy intensity scenario.

2) **A lack of financing models (ESCOs)**: A lack of ESCOs in the Irish market impacts the potential of client's budgets to meet the additional capital expenditure required to achieve NZEB retrofit (5.6), thus potentially impacting the use of energy conservation measures in the retrofit design process.

3) **Inappropriate economic analysis tools:** Payback periods for energy conservation measures are often analysed in isolation from the remaining lifespan of the existing building. This biases decision making toward shorter lifespan less costly active measures and away from longer lifespan fabric measures. As existing building envelopes approach the end of their technical lifespan, at 40 years, when elements such as flat roofing, seals, windows and cladding all start to fail, this requires either the demolition and replacement of the building, or its renovation. When budgeting a retrofit, clients often do not equate retrofit investment with replacement investment, despite equivalent additional lifespan. In the RTC retrofit case studies this can arise through the lack of use of Scenario Analysis and Net Present Value.

4) **Low use of scenario analysis tools:** In RTC case studies, scenario analysis tools have been demonstrated to improve client goals beyond minimum regulated standards. Scenario analysis can inform investment decision-making and establish goals and targets for the design stage.

5) **Low Energy retrofit is more challenging than new build:** Low energy building decision-making is complex and dependant on multiple interdependent criteria that can cross-disciplinary boundaries, impacting both energy consumption and environmental performance (Ma et al. 2012)[591]. In retrofit, decision making criteria are made more complex by the building typology, fixed aspect, volume, fabric deterioration and the weather exposure of the existing building, which can increase risks and limit design solutions.

6) **Poor Interdisciplinary communication:** The effective evaluation of all decision-making in the design process (Lewis 2004) is impacted by the iterative nature of the design process (Lawson 1980). The subdivision of roles could be leading to silo based decision-making and communication problems (Becker 1999). The

lack of both socio technical platforms (Haymaker et al 2010) and cross disciplinary knowledge of whole building performance could be leading to poor decision-making, fundamental errors and risk in low energy building retrofit.

7) **Low use of Building Performance Simulation (BPS) tools:** Survey results indicate a low adoption of Building Performance Simulation (BPS) tools in Ireland amongst architects to validate design decisions and a dependence on elemental backstop values and *Acceptable Construction Details* (ACDs). Common BPS tools like IES used by engineers do not model for thermal bridging or interstitial condensation risk associated with architectural detailing of the façade, potentially leading to demarcation, communication and performance issues for building retrofit.

8) **Low use of Post occupancy performance/energy performance validation:** RTC retrofit case studies have demonstrated a low use of post occupancy performance and energy measurement-validation in a typical Irish design process.

9) **Truncated design process**: Pre-design, simulation performance and post occupancy/performance validation stages are largely absent from the RTC socio technical building design process which may reflect on the wider context of non-residential building retrofits in Ireland. These stages would require additional time and skillets to the standard design process. In the context of achieving a validated NZEB building retrofit performance, the socio-technical system for RTC retrofits would need to broaden to augment the design process with pre-design, simulation, and post occupancy stages. The commonality of the issues discovered may infer that such a broadening of the socio-technical system for building retrofit may be applicable to a wider range of building non-residential typologies within public ownership.

The systemic barriers to NZEB retrofit adoption in Ireland prompted the research question RQ5: **"How can we adapt the design process in Ireland to meet the intentions underlying the EU Directive on near zero energy buildings?**

Having established the external factors that drive the goals and performance targets for retrofits, and the systemic barriers to NZEB retrofit in Ireland, the research in this chapter examines whether such an augmented socio-technical design process in Ireland could deliver NZEB retrofit performance and explores key areas within the process for improvement. A pilot project (referred to as Phase 1 or the Zero2020 project) was carried out in 2012 targeting a measured NZEB retrofit performance. The Phase 1 project was supplemented by researchers acting as client side expertise to augment a professional design team's stages in planning, design, risk analysis and post occupancy evaluation/validation addressing key barriers identified in the research. A very similar Phase 2 project (standard run) for the retrofit of the same building at a similar scale was carried out in the same year to comply with contemporary legislation, subject to normal market conditions demonstrating a normal design process, without researcher augmentation. Phase 1 is referred to as a 'deviant case' (Silverman 1993) and Phase 2 study is referred to as the 'standard case'. The cases are analysed using mixed method research[16] to map the relational networks of the socio technical design process, identifying key thematic barriers within the system to achieving NZEB retrofit performance of RTC buildings.

7.3 A literature review of design process models for low energy retrofit

The design process cannot address all of the 9 system barriers outlined above. System issues such as low intensity regulations (1) and a lack of ESCOs (2) are beyond the design process demarcation. System barriers

[16] A mixed method approach can include both qualitative and quantitative research. This research includes action based research, , case study analysis, literature review, questionaires, interviews and qualitative content and thematic analysis of case studies.

3 and 4 impact pre-design stage financial analysis decision-making and the use of energy conservation measures in retrofit strategies. System barriers 5-7 impact design stage decision-making and barrier 8 impacts the post occupancy stage. Barrier 9 highlights the truncated nature of the design process where pre-design and post occupancy stages have a low level of adoption in the socio-technical process for building retrofit in Ireland.

This thesis has examined the barriers to low energy retrofit and proposed improvements to the socio technical design processes for the deep retrofit of buildings in chapters 5 and 6. Such processes has been previously been explored and mapped by Santamouris et al (2007)[592], ARUP (2009)[593], Juan et al (2010)[594], Chidiac et al (2011)[595], Ma et al (2012)[596], Kumbaroglu & Madlener (2012)[597] in different regional contexts based on a variety of building typologies.

Santamouris et al (2007) carried out the retrofit of a green roof system to a nursery in Athens (Greece) to reduce surface conductive heat gain in summer. In this study physical environmental conditions are measured over a three-month period, and are compared against dynamic simulation modelling (using Tynsys 5.1). The correlation of simulation and physical measurements supported a comparison of external insulation retrofit (including a green roof) to an existing building. The results demonstrated a significant reduction in cooling loads in summer and a modest reduction in heating loads in winter. The decision-making does not quantify the financial investment or compare operational cost savings. The decision-making matrix is limited design support tools for building performance simulation and to pre-design stage financial analysis.

Kumbaroglu & Madlener (2012) analyse the financial decision-making tools for retrofit investment, examining energy price fluctuations, adopting a discounted payback period rule (i.e. accounting for the time value of money) and net present value calculations (NPV) for the existing condition of the building and its services equipment. They find that “ improving the thermal properties of a building’s envelope (roof, external walls, windows, doors, and floors) is typically one of the most economical ways to reduce its energy needs under constant operating conditions” where “energy price increases remain moderate and smooth”. They do however warn that retrofit investment costs may not be recovered sufficiently by rent increases (up to 11%) Kumbaroglu & Madlener (2012). The decision-making matrix is limited to pre-design stage financial analysis.

Chidiac et al (2011) established baseline energy performances using EnergyPlus simulation software for a number of building typologies built before and after 1975, highlighting typical energy performances of various services equipment. The paper focuses primarily on financial investment decision-making of each energy conservation measure largely ignoring environmental conditions. Where it found that roof insulation, lighting and boiler upgrades had acceptable payback periods; it did not factor in the impact of maintenance costs on services upgrades. Whilst it did include Net Present Value analysis it found that external insulation upgrades had pay back periods exceeding 100 years. The decision-making matrix is limited to pre-design stage financial analysis.

An ARUP (2009) report[598], based in a UK context, addressed a wide range of investor and landlord concerns with split incentives, refurbishment cycles and added capital value of properties. It proposed a simple 5-step approach to retrofit which focuses on the pre-design stages, establishing baseline performance using energy, waste, water, environmental audits and occupancy surveys. Simple accessible visual diagrams (Fig 7.1) offer investors decision-making tools where levels 4 and 5 involved fabric retrofit. ARUP introduce 25 non-energy targets to consider in decision-making but doesn’t offer any matrix for assessing these criteria. In assessing the financial costs of the investment, they adopt a simple payback methodology with operational cost savings. The decision-making matrix is limited to the pre-design stage but provides some valuable stages in the decision-making matrix.

Building performance	Building condition: Excellent	Good	Poor	Very Poor
Excellent	Maintain	Level 1	Level 2	Level 3
Good	Level 1	Level 2	Level 3	Level 3
Poor	Level 2	Level 3	Level 3	Level 4
Very Poor	Level 3	Level 3	Level 4	Level 5

Fig 7.1: Examples of the degree of intervention for each level of refurbishment (based on BSRIA, 1998, and BRE, 2000)(ARUP 2009)[599]

Juan et al (2011)[600] puts forward a decision-making matrix (Fig 7.2) for the building retrofit of a 1979 storage building in Taiwan including a three-step process; setting goals, identifying strategies and adopting scenario analysis. The main thrust of the paper analyses the environmental rating of the retrofit across a range of sustainability criteria developing an algorithm for suggesting combinations of energy conservation measures. Again the decision-making flow diagram is limited to building performance simulation and to pre-design stage financial analysis, but the mapping of decision-making does contribute to a hierarchical series of related inputs and assessments, demonstrating the collective complexity and inter-reliance of decision-making on overall performance.

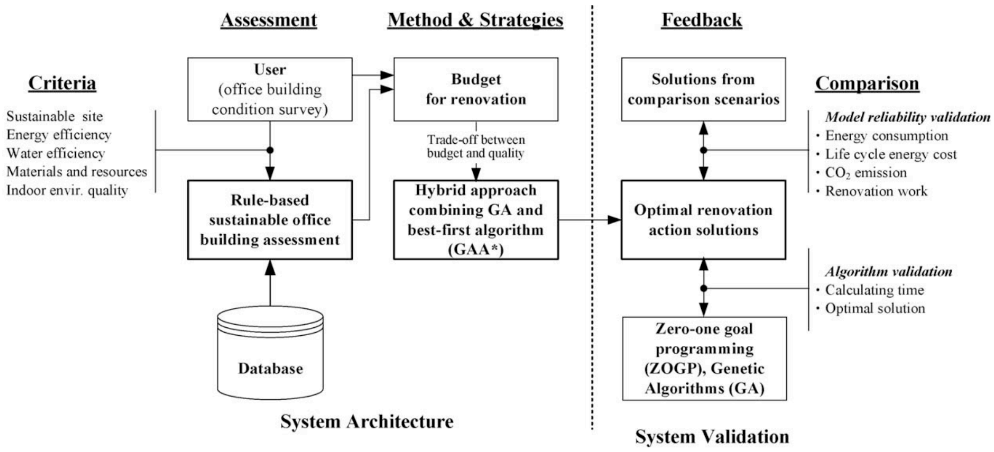


Fig 7.2 Flow diagram of decision support system. (Jual et al 2010)

Supporting an algorithmic approach in the search for optimal ECM solutions, Ma et al (2012) writing in a Hong Kong regional context offers an insightful overview of the existing literature on low energy retrofit arising from his 2008 thesis on retrofitting chilling systems (Ma, Z., 2008)[601]. The paper breaks a sustainable retrofit program down into 5 stages (fig. 7.3). The complex nature of ECM selection and interactive nature of subsystems in a retrofit create a "multi-optimisation problem". Ma et al (2012) highlights the importance of taking a model-based approach, where ECMS can be identified, supported by simulation tools and economic assessment of ECM options. Of all the papers Ma et al (2012) offer the most global overview of the retrofit system, mapping steps from pre-design to post occupancy rather than being solely focused on decision-making around optimal ECM selection. Drawing from Remer and Nieto (1995) the paper critiques the validity of Simple Payback period economic analysis, identifying "that NPV is the most typical technique for optimal building energy assessment among 25 techniques…[which] in turn aids the decision support process in making an optimal design of building retrofits" (Ma et al 2012). Finally the analysis of existing research highlights that there is a reliance on numerical modelling rather than validated post occupancy energy savings to support findings. Ma et al (2012) highlighted that "more research and application work with practical case studies on commercial office building retrofits is essentially needed. This can help to increase the level of confidence of building owners to retrofit their buildings for better performance."[602]

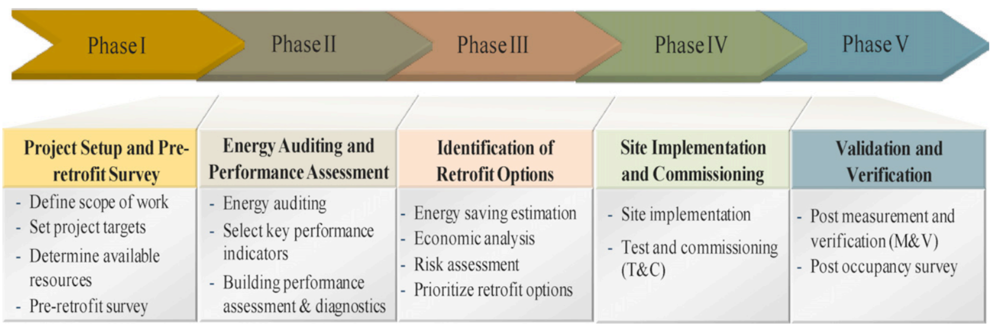


Fig. 7.3 Key phases in a sustainable building retrofit programme (Ma et al 2012).

The next section addresses these concerns by exploring both design processes and validated real world energy performance from an NZEB retrofit.

7.4 A systematic socio-technical NZEB Retrofit process

Supported by the socio-technical theoretical systems reviewed in the previous section (7.3), the "**Outline** Socio-Technical System Deep Retrofit" (Fig 7.4) expands the theoretical systematic approaches, proposing a 4-stage pre-design, design, construction and post occupancy process. The stages are deliberated separated to allow for external consultants to the design process to support strategic decision making at the front end of the system and to analyse the performance at the back end of the system. This creates both a learning cycle and a set of professional services separate from that of the standard design process allowing 'specialist' experts (Brown & Duguid 2000[603], Hammer & Champy 1993)[604] to support processes where experience understanding and knowledge is not ubiquitous amongst design practices. The mapping experience is adapted from the "systematic approach to sustainable building retrofit" by Ma et al (2012), the "Architecture of decision support system" (Jual et al 2010) and ARUP (2009) "Five simple steps to a survival strategy for your building". The theoretical "**Outline** Socio-Technical System for Deep Retrofits" is now compared against applied case studies (Phase 1 and Phase 2) to validate the process or identify gaps.

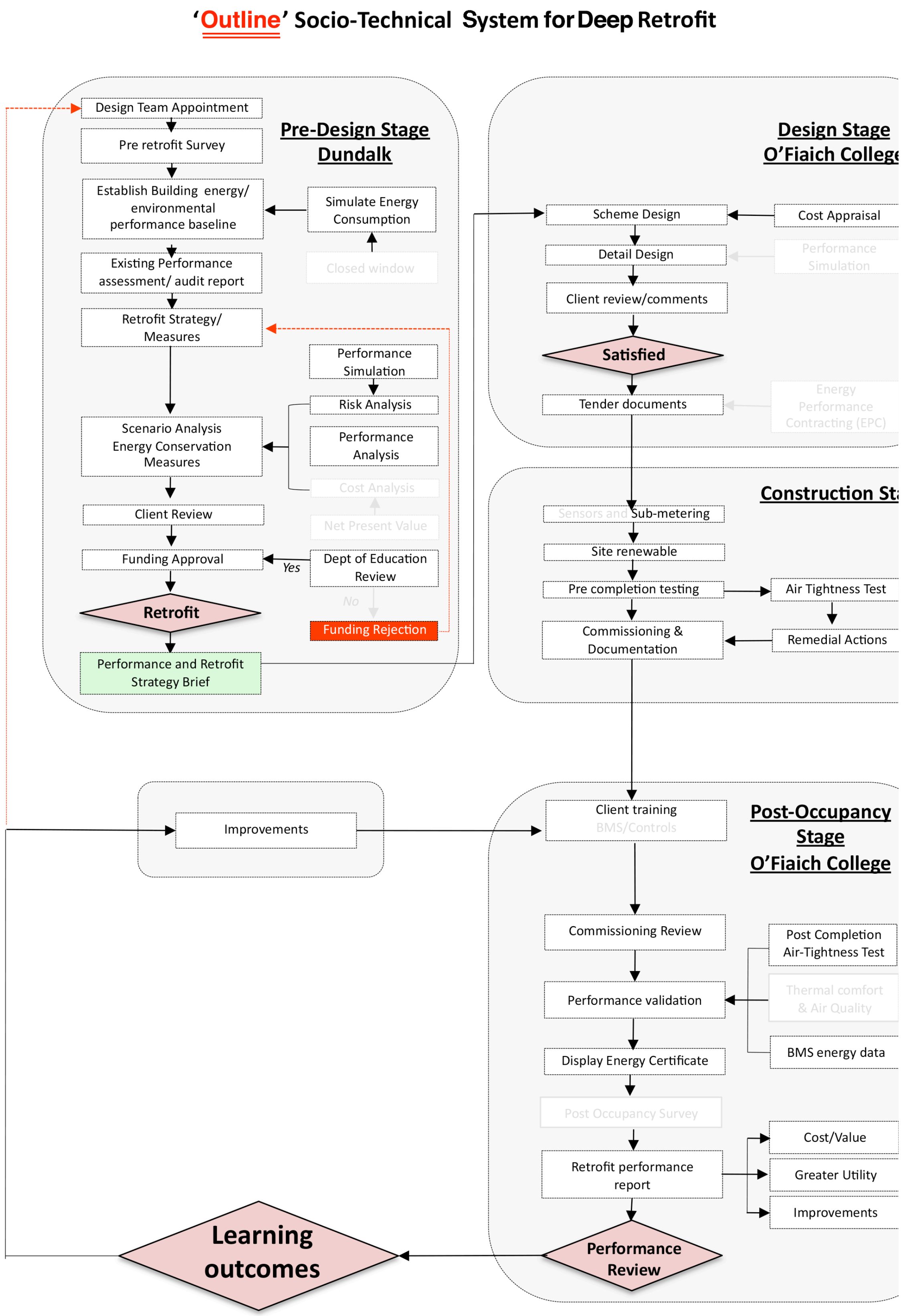


Fig. 7.4 '**Outline**' Socio Technical System for Deep Retrofit (Ó'Riain 2016)

7.5.1 Method 1: Case study analysis, sample selection

The case studies selections were based at Cork Institute of Technology, and are not a random selection. They are typical examples of a previously un-retrofitted RTC building beyond its 40-year lifespan with a failing envelope. Although Cork is the largest of the original RTC typologies built in 1974 over 27,000m^2 in 4 finger blocks running east west, it is also one of the largest examples of the common typology, without any significant major changes or retrofits since its original construction. The precast concrete construction method is very common to public non-dwelling buildings developed in Ireland in the 1960s and 1970s. Two cases study are carried out on retrofits to a sample selection of this building. The first case study (Phase 1) built in January 2012 over 250m^2 of the first floor of Block B. The second case study (Phase 2) was a similar scale project to the ground floor of the same area of Block B, with the same design team (as Phase 1, with the exception of the Engineer), was built subsequently in June 2012.

The first case study; Phase 1 (also referred to as Zero2020) was a retrofit carried out in 2012, with project targets and goals set at estimated NZEB performance targets (known at that time). The project followed the pre-design stages of the "systematic approach to sustainable building retrofit" (O'Riain 2016). The researchers provided the 'specialist' skillets developing an NZEB strategy, proposing energy conservation measures (ECMs), surveying buildings, examining relevant precedents, auditing existing energy/environmental performance and modelling proposed retrofit performance. The research team would also provide post occupancy stage supports in Phase 1. The researcher's specialist services also supported the design stage with simulation modelling and performance validation tools to the design team where they were absent or lacking. Pre-design and post occupancy stage supports were removed at Phase 2 to examine the differences in processes and performances of a standard run design process.

The process is recorded and analysed to address systematic gaps in a ‘routinized’ (Brown & Duguid 2000)[605] design process based on RTC building retrofits in Ireland, subject to its economic, legislative and climate context. Phase 1 is recorded through design team minutes, emails, communications, observation, reports and a survey of the participants.

Phase 2 (a subsequent RTC retrofit at the same site) becomes the **Standard Case** for analysis (Silverman 1993)[606]. It represents is a more typical situation, which may capture a more reflective characteristic of the heterogeneity of the general population of design practice in Ireland in 2012. In this case the same client and design team (as Phase 1) have an immediate and relevant precedent, experience and tacit knowledge to draw on. Phase 2 is recorded through design team minutes, emails and an interview with the project manager.

7.5.2 Method 2: Qualitative Content Analysis

The socio-technical structure of the design process and the community of practice are examined in an Irish context, to identify ways to improve energy performance outcomes through improved communication, supports, augmentation or modifications to the design process in the context of RTC retrofits.

Drawing on Kolb’s (1984) cycle of experiential learning and Lawson’s route maps of the design process, the chapter maps decision-making, group dynamics, group activity, faults and gaps in design practices, whilst examining the aspirations, motivations, intentions of stakeholders and the practices of the design team.

Qualitative content analysis is adopted (see chapter 2, Methodology for more detail) “to provide knowledge and understanding of the phenomenon under study” (Downe-Wamboldt 1992[607], Hsieh & Shannon 2005[608]). Much of the correspondence examined include decisions and record actions in a de-personalised voice, without full transcripts of individual discussions. Therefore in content analysis it was not possible to deduce meaning in the use of language. To deduce meaning, content analysis, instead focuses on identifying power and understanding the dynamics of relationships within a complex community of practice (Wenger 1998)[609]. A deductive approach (Mayring 2000)[610] was taken to validate or extend the theoretical framework developed from existing literature (Hsieh & Shannon 2005[611]). A deductive approach allowed for the initial categorised and sub categorised of communications into the 2278 codes. Codes are grouped into themes and the relationship between themes help advance theories, support and further develop existing evidence of barriers to deep retrofit, and refine the 'Outline' Socio Technical System for Deep Retrofit.

7.5.3 Participant Roles & responsibilities

The client, Daithi Fallon, initiated the project, directing funding decisions and liaising with the CIT Estates/Facilities and the Department of Education. The head of CIT's Estates Department, Kevin McCarthy, set down limitations for retrofit solutions to the research team, managed the tender and appointment process, appointing an Employer Representative (ER), Susan Brennan, for the construction phase. The ER would chair weekly construction stage meetings between the design team and the builders, and ensure that all safety and documentation procedures were followed.

The research team was made up of Researcher 1 (Marc Ó'Riain), Researcher 2 (Paul O Sullivan) and Researcher 3 (Fergus Delaney). The research team represented a cross disciplinary group interested in various different aspects of the project. They brainstormed initial ideas, drew up the performance brief, developed an initial retrofit strategy, helped secure funding, ran design charrettes, carried out energy audits, recorded environmental conditions, liaised with the design team in arriving at a design solution, provided supporting simulation modelling to improve design detailing, observed interactions, highlighted potential problems, monitored construction/commissioning and measured the post occupancy energy and environmental performances. Researcher 1 (Marc Ó'Riain) carried out precedent studies, building surveys, assisted in energy audits, provided simulation support for thermal bridging and hygroscopic transfer, using primarily LBNL Therm 5 and Fraunhofer WuFI. His research interest was with design systems for NZEB retrofit, energy conservation measures and embodied energy in building retrofit. Researcher 2's(Paul O Sullivan) research interest was in ventilation of free running buildings. He provided energy-auditing, simulation of overall building performance using TRNSYS-17 and calculations for ventilation. Researcher 3 (Fergus Delaney) whose research interest as a building services engineer was BMS active systems, environmental monitoring and renewable energy technologies. He installed environmental monitors, measured conditions, coordinated BMS commissioning, had an involvement in air source heat pump and photovoltaic installation. Researcher 3 was responsible for the measurement and validation of the post occupancy performance. All three researchers worked collaboratively through the project publishing a conference paper together on its quantitative performance outcomes[612]. Researcher 4, Cian Ó'Driscoll, was not part of the initial project, but subsequently carried out post-occupancy user analysis a year after the construction phase.

Daithi Fallon, acted as the Client Team Leader and aided in securing funding. The client team leader provided decision-making and direction during Phase 1.

From appointment, March 2011 the design team leaders were ARUP, led by John Burgess as the design team leader. ARUP (Kevin O Halloran) also provided IES (Apache Sim) Simulation modelling for heat gain, solar penetration and estimated energy consumption. ARUP were also responsible for commissioning of active systems.

The Quantity Surveyor (Finbar Jennings) was appointed to estimate the costs of design iterations.

The Project Architect (Turlough Clancy) from Henry J Lyons was appointed in June 2011 to develop the façade design and detailing after ARUPS had developed an initial schematic. Architectural Metal Systems (AMS) supported the Project Architect, in developing the thermally broken external cladding frame and simulating thermal bridging performances. The architects did not carry out simulation modelling of junction detailing, but relied on AMS for junction modelling for thermal bridging. Zita Pearce (Punch), John O Connell (ARUP), and Bertie O'Connell (ARUP) provided support to the project but were not heavily involved in day-to-day communications and decision-making. Jim O'Sullivan was the main contractor (builder) and carried out all work on site for Phase 1 from December 2011 to May 2012.

7.6 A synopsis of Phase 1

Phase 1 (Case 1) is the deviant case, where supports and process stages are provided to augment the design process to NZEB performance in line with EPBD aspirations.

Data collection

Phase 1 communications with all stakeholders was recorded from its initiation in November 2010, to its realisation in May 2012, and through its monitoring/ validation stage, in December 2013. Communications and notes were logged, and records were kept on a daily basis, recording progress, observations and insights (Appendix 7.1). A video log records the build stage, and a photographic log records the build on a daily basis; these were published on a concurrent research project website (Zero2020energy.com) for dissemination purposes to industry. The Phase 2 project and its communications with all stakeholders were recorded from its initiation in May/June 2012, to its realisation in September 2012.

Phase 1

The stakeholders involved the client team, a client side specialist expertise team (the research team) a design team and contractors. Each team was experienced in construction to building regulations.

The client team appointed the research team for Phase 1 to help develop a performance brief and appoint a design team. The client team set key physical restrictions to retrofit solutions and budgetary/logistical limitations to the research team. The research team followed the stages set of in the "Socio-Technical System for NZEB Retrofits".

"Cork Institute of Technology occupies 27,000m^2 of an existing two-storey, precast concrete structure, set out in 4 main finger blocks" (Hyde et al. 2013)[613], running east to west (Fig. 7.3). The low-rise grid-optimised modular concrete structure is located in the south of Ireland, with a temperate oceanic climate.

Phase 1 (the Zero2020 project) involved the appointment of a research team in October 2010 to develop a performance brief for the low energy retrofit of 250m^2 area of the 1st floor of a low-rise grid-optimised modular concrete structure, built in 1974 as a RTC building. The project targeted a Net Zero Energy Building Performance through retrofit in line with EPBD aspirations. In the absence of EPBD performance targets (2012) the researchers established performance targets and goals in line with an NZEB energy conservation strategy, with energy balance to be met by onsite renewable energy. The project performance brief outlined a number of Energy Conservation Measures (ECMs) along with fabric elemental targets (FETs) (Table 7.2) derived from the Max Fordham Sustainability Matrix for School buildings (Fordham 2011)[614].

Comparison of Elemental targets					
	Part L 2008 W/(m^{2}K)	**Coady/ARUP 2011** W/(m^{2}K)	**Fordham Index 2011** W/(m^{2}K)	**Passive House 2011*** W/(m^{2}K)	**Zero2020 Targets** W/(m^{2}K)
Roofs (flat)	0.22	0.16	0.1	0.15	0.1
Walls	0.27	0.2	0.1	0.175	0.1
Ground Floors	0.37		0.1	0.15	n/a
Windows	2.2	1.3	0.8	0.8	0.8
Air Tightness	10 m^3/h/m2@50pa	5 m^3/h/m2@50pa	1 m^3/h/m2@50pa	0.6 m^3/h/m2@50pa	1 m^3/h/m2@50pa

Table 7.2 Comparison of elemental targets considered (Ó'Riain 2015).

The research team carried out extensive physical surveys of the existing building and its precedents, identifying poor indoor environmental thermal comfort (TC) conditions, high humidity, condensation, a high incidence of radiant thermal asymmetry (RTA), high air infiltration, a low level of mechanical control and energy consumption in line with precedent RTC case studies. A high level of envelope related heat transfer could be related to the poor level of insulation of the building fabric, the high percentage of single glazing, the high degree of air infiltration and a poor level of heating control.

This resulted in the high space heat demand recorded in an energy audit, and a high frequency of overheating in summer. The building survey highlighted that the existing concrete external cladding was suffering from depassivation and expansive spalling due to water ingress over its lifespan, with frequent delamination of panels from the internal structure. The original panels were separated from a thin (100mm) internal block wall by a well-ventilated cavity (effectively eliminating the external panel as an insulation layer). The research team also carried out an energy audit from billed data and building management system (BMS) data establishing baselines of performance for the building fabric, environmental conditions and energy consumption. The research team simulated a proposed energy performance based on conservation measures and elemental targets and reported this to the client in an energy audit report (Table 7.3).

Comparison of Energy Consumption Kwh/m²a					
	Cork RTC 1974 Building metered data 2011 Delivered Energy kWh/(m²a)	**Cork RTC 1974 Building metered data 2011 Primary Energy** kWh/(m²a)	**CIBSE TM46 2008 Primary Energy** kWh/(m²a)	**Passive House 2013 Enerphit Primary Energy** kWh/(m²a)	**Zero2020 Targets Primary Energy** kWh/(m²a)
Electricity	109	284	80	51	40
Heating	99	104	240	25	25
Total	**208**	**388**	**320**	**76**	**65**

Table 7.3 Comparison of building delivered energy consumption, guidance and targets (Ó'Riain 2015).

Based on the high heat loss through the envelope, the deteriorating of the envelope and the poor thermal comfort conditions, a primarily passive approach was selected together with natural ventilation strategy[17]. The Energy Conservation Measures (ECMs) that arose from this strategy included a minimisation of heat demand through external fabric insulation, high performance glazing, high and low (manual[18] and automated vents), the use of exposed thermal mass to shift the Diurnal heat cycle[19], separating the Phase 1 space from the existing uncontrolled heating system, and supplementing remaining heat demand with an air source heat pump[20]. Daylight sensors, proximity sensors, sub-metering, low energy lighting[21] were included to moderate electrical demand but low energy lighting had been installed in the existing space in 2009. The selection of a renewable energy source would be left to phase 3 after the measurement and validation phase to identify the most suitable source to meet remaining energy demand. Precedent studies had identified risk of lichen growth and possible delamination issues with applied external insulation cementitious render systems at O'Fiaich College, by Johansson

[17] The Department of Education guidelines for school design favour *non forced-air* design solutions, making a natural ventilation solution more scalable, if the technical question of NZEB performance could be solved in this context.
[18] For local user control of their immediate working environment
[19] Effectively shifting overheeating to outside occupied hours and moderating the variation in internal temperature extremes.
[20] Scaled to allow for expansion to Phase 2
[21] An energy perfomance of approximately 65 lumens/watt was initially targeted

(2011)[615] and the potential for interstitial condensation from the Dundalk IT retrofit report by Faber Maunsell (2005)[616].

A Net Present Value (NPV) calculation for the existing building indicated that the building had reached the end of its functional and financial lifespan, and the client team should consider re-investment strategies in line with depreciated replacement cost. A depreciated replacement cost calculation indicated that the replacement cost current market cost was €2400/m^2 plus demolition and disposal costs at 300/m^3. In 2012, the final report (Hermelink et al., 2012)[617] defining the principles of EPBD performance, estimated the 30-year lifetime investment cost for NZEB new build to be between €2397-€2756/m^2 (Table 7.4).

"benchmark area"	Min	Max
Range of NET primary energy [kWh/m^2y]:	0	15
Range of Global Costs over 30 years [€/m2]:	2397	2756
Number of Building Variants:	189	

Table 7.4 Benchmark zero energy building global costs over a 30-year period (Hermelink et al. 2012)[618].

According to AUDE (2008), energetic retrofit should be budgeted at 80% of new build costs (McKerracher and Forbat 2008)[619]. Therefore, an appropriate budget for NZEB retrofit should be 80% of the median cost of Table 7.4, or €1918-€2205/m^2. The client reviewed the proposal and agreed to tender for a design team and approved an initial budget of €250k (approximately €1000/m^2) with a view to seeking more funding through SEAI grant assistance targeting €2000/m^2 including research instrumentation. The research team then developed a performance brief, with agreed targets and goals, for tendering for a design team project leader to explore the feasibility of the project. The client team elected only to appoint an engineer (supported by a QS) at this point rather than a full design team to develop the proposed ECM retrofit strategy. The research team developed a tender performance brief for design stage professional services, for the client, to include performance validation of design schemes, simulation and scenario analysis.

ARUP, who had worked separately on the separate feasibility plan for RTC retrofit with Coady Architects in 2011, were appointed as project leaders in March 2011[22]. ARUP had worked continuously with the Cork College since 1974 then and therefore had a high level of tacit knowledge of the building.

ARUP schematically tested the ECMs with various fenestration arrangements, simulating heat gains and heat demand based on proposed elemental fabric performances. ARUP however did not carry out a cost benefit analysis and risk analysis of thermal bridging or interstitial condensation. Scenario analysis was not carried out, unlike case studies reports from Letterkenny 2002 and Dundalk 2005. Initial budgets were beyond the intended grant aid funded project budget, thus resulting in multiple interactions to the design scheme, with various ECMs costed and revised without performance validation. The lack of scenario analysis an early stage validating strategies and budgets created conflicts, delays and a potential performance gap. IES Simulation was too slow to inform the iterative changes in the various design schemes. The lack of a fixed client side budget extended the design period and delayed the final design proposal.

Risks associated with an applied cementitious render system would retard the staged retrofits in winter inter-semester breaks and result in potentially high maintenance costs. Thus an external thermally broken insulated frame was selected, with supplier support, suiting client aspirations for modular staged roll out. This specific ECM required an Architect (appointed in June 2011) to supplement the design team in order to develop the proposed façade strategy and accurately cost an

[22] This was at the height of Ireland's recession, and proposed fees were viewed as very competitive.

externally insulated cladding. Schematic designs for the cladding were developed and delivered by the architect and a cladding supplier, in September 2011. Risk assessment of the proposed schematic by the research team identified conductive and convective heat loss risk at 10 key linear junctions as well as serious air tightness issues in the proposed scheme. An air tightness assessment further highlighted weaknesses in the proposed scheme. The final design Energy Conservation Strategy was based on:

Passive Energy Conservation Measures

- A super-insulated external insulated modular frame suiting staged retrofits
- Roof Insulation and weathering
- Electro-chromic glazing with varying *G-Factors*[23]
- The use of thermal mass to moderate temperature fluctuations (CIBSE, 2006)[620]
- Night Purge Cooling
- Single sided manual natural ventilation panels louvers

Active Energy Conservation Measures

- Low-energy lighting,
- Occupancy and environmental sensors,
- Automated natural ventilation panels louvers
- Low temperature radiators
- Air Source Heat Pump
- Building Management System

A performance report based on simulation modelling by ARUP validated whole building performance but lacked risk analysis of thermal bridging or interstitial condensation. Researchers carried out thermal and hygroscopic risk analysis to mitigate heat loss issues and

[23] *The solar factor (or G-Value) measures the percentage of heat that passes through the glass. The lower the solar factor the higher the solar protection and therefore the higher the performance of the solar control glass. (Saint Gobain 2016)*

validate that moisture trapped in the existing cladding would not represent a risk in the scheme. Amendments were made to the scheme design to address thermal bridging issues and moderate air tightness detailing. The decision to remove plaster finishes from the internal side of external walls placed a high risk to meeting performance targets. Daylight sensors were removed from the scheme by the design team, in isolation from client review, again potentially impacting electricity demand.

The client approved the final scheme for tender and additional funding was secured from the Department of Education in November 2011 to meet a €1892/m^2 in line with AUDE estimates[621]. Construction work began on site in January 2012 with weekly site meetings. The client appointed a client side Architect as the employer representative (ER) to run the construction stage.

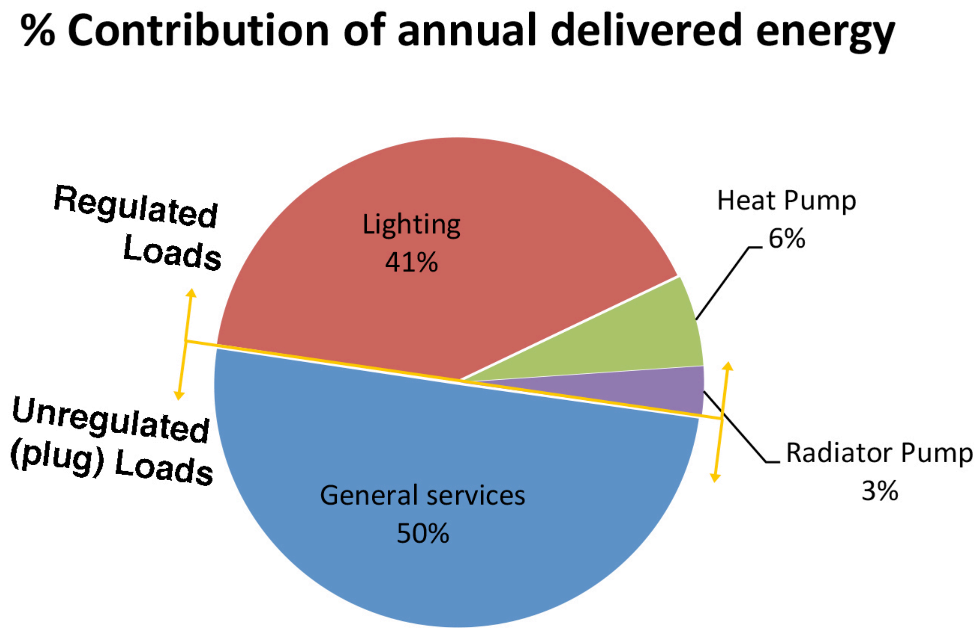
The construction stage saw no increase in design team inspections beyond normal practice. The design of concrete ground floor foundation pads by the Architect and structural engineer showed little awareness for implications of thermal bridging at Phase 2. Daily researcher team inspections recording the progress and highlighted quality control issues during construction. A pre-completion air tightness test highlighted a number of quality control issues with air tightness and a greater amount of air infiltration to through internal services penetrations and external wall. Remedial actions improved air tightness from 1.96 $(m^3/hr)/m^2$ at 50Pa to 1.76$(m^3/hr)/m^2$ at 50Pa but did not meet pre-design stage targets of 1 $(m^3/hr)/m^2$ at 50Pa. A number of pre-completion issues arose around the specification of roller blinds by the architect, which covered ventilation louvers. These had to be replaced with individual window blinds on the north façade.

Phase 1 construction stage completion occurred in May 2012, with commissioning issues arising with active systems (BMS, ASHP &

actuated ventilation louvers) delaying full functionality (for measurement and validation) until September 2012 (fig 7.5). Researcher 3 provided support to ARUP in commissioning with no involvement from the Architects post occupancy.

Figure 7.5: Block B CIT Phase 1 first floor (left) and Phase 2 (right) ground floor retrofit (photos: O'Connell 2012/13).

The BMS monitoring was recorded and reported by Researcher 3, the building services engineering researcher, over the calendar year 2013. Issues of power outages illustrated the need for regular inspections. A different architectural researcher, Researcher 4 carried out, a user-satisfaction survey in 2013.



Graph 7.1. Percentage contribution of post-occupancy delivered energy (Delaney 2014).

Phase 1: Validated Energy Performance

A final retrofit energy[622] and environmental[623]report was published in 2014 with a research team peer reviewed conference paper in 2013[624], and a published peer reviewed architectural researcher conference in 2014[625]. Measured and validated primary energy performance results (Table 7.5) demonstrated regulated nZEB performance. Excluding general services (unregulated loads), the Zero2020 project has a measured primary energy consumption of 85.5 kWh/m^2/yr (based on 2021 degree days, in line with CIBSE TM46) (Table 7.5). The fixed electrical lighting demand was 75% higher than simulated pre-retrofit projections. However, thermal energy demand was 40% lower, and comparable to Passive House or EnerPHit standard. Although measured air tightness performance was well outside pre-design stage targets, space heat demand (16 kWh/m^{2}yr) was well below pre-design stage projections and in line with Passive House (15 kWh/m^{2}yr) performance targets.

Service	Delivered energy kWh/m^2/annum	Primary energy kWh/m^2/annum	CO_2 Emissions kgCO_2/m^2/annum
General Services	35.1[*1]	86.0	31.2
Lighting	28.4	69.5	15.7
Heat pump	4.2	10.3	2.3
Radiator pump	2.3	5.7	1.3
Total	70	171.5	38.8

*1 The delivered energy for general services in ZERO2020 excludes energy consumed by a 3D printer which used on average 392 kWh per month

Tables 7.5 Phase 1 (Zero2020) Delivered Energy 2013 (Delaney 2014).

This result (Table 7.6), based on a single year of data, represents a 74% delivered energy saving (directly impacting operational costs) over pre-retrofit regulated energy performance data.

	Delivered energy $kWh/m^2/year$	Primary energy $kWh/m^2/year$	CO2 $kgCO_2/m^2/year$
Pre-retrofit	185.0	325.0	69.2
ZERO2020	70[*1]	171.5	38.8

Table 7.6. Phase 1 (Zero2020) Pre- and post-retrofit primary energy performance (Delaney 2014).

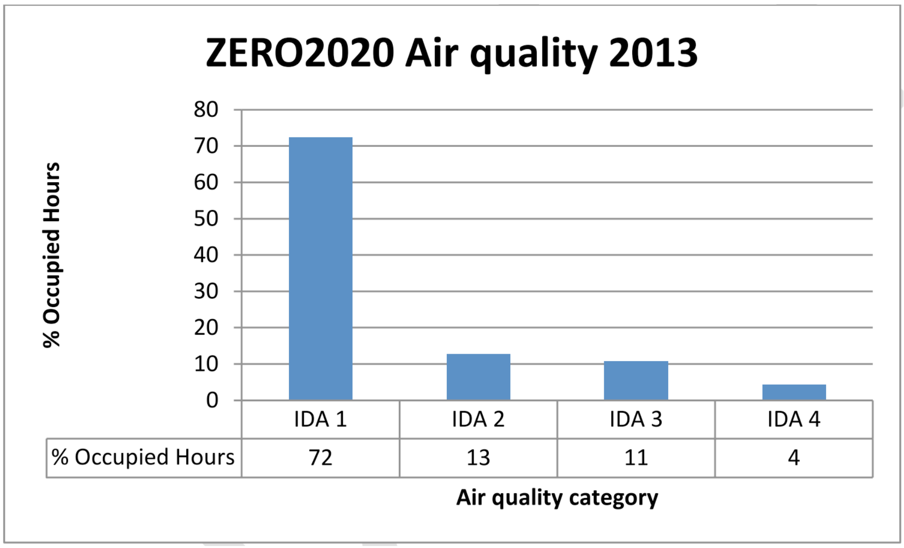
Following the validation and measurement reports in 2014, delivered electrical energy was 90% of the total energy demand mix, leading to the installation of a PV array to offset the entire remaining energy balance of the nZEB[24] building, resulting in a **Net Zero Energy performance (<u>NZEB</u>)**. Unregulated loads (Table 7.5 general services moved from 30% of the total energy demand mix to 50% of the total energy demand mix of an NZEB building. The scale of the PV array also met general services demands. The validated environmental performance (Tables 7.7 & Graph 7.2) reported CIBSE required ventilation rates achieved by categories IDA 1 and IDA 2 satisfying this condition for 85% of the time.

EN 13779:2007 **CO_2-level in rooms**

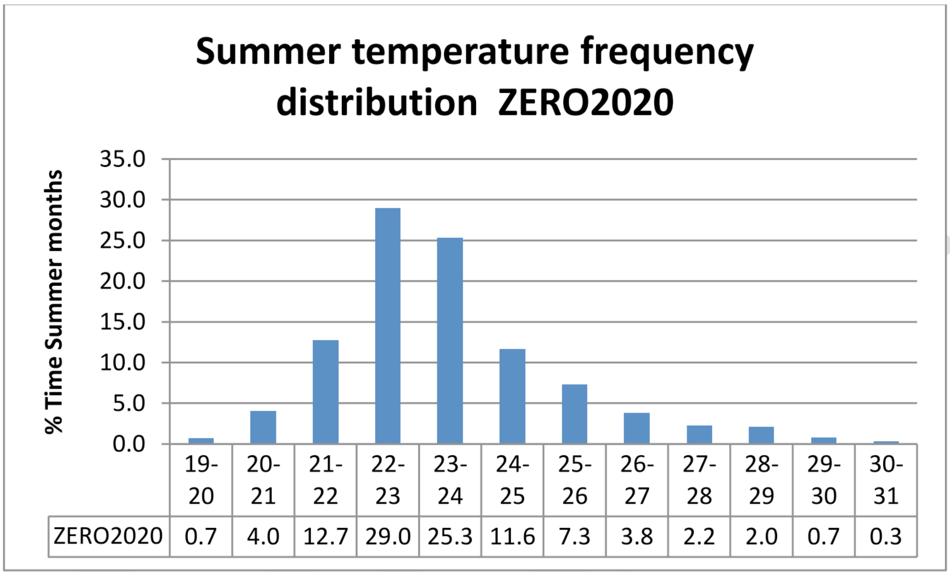
Category	CO_2-level above level of outdoor air in ppm	
	Typical range	Default value
IDA 1	≤ 400	350
IDA 2	400 – 600	500
IDA 3	600 – 1,000	800
IDA 4	> 1,000	1,200

Table 7.7. CO2-level above level of outdoor air in ppm (EN 13779:2007 Table A10)[626]

[24] An nZEB is a nearly Zero Energy Building with a balance of energy consumption yet to be met by site renewable energy. An NZEB is a Net Zero Energy Building where the energy balance has been met by site renewable energy.



Graph 7.2. Phase 1 (Zero2020) Measured air quality standards: CO2 (Delaney 2014).

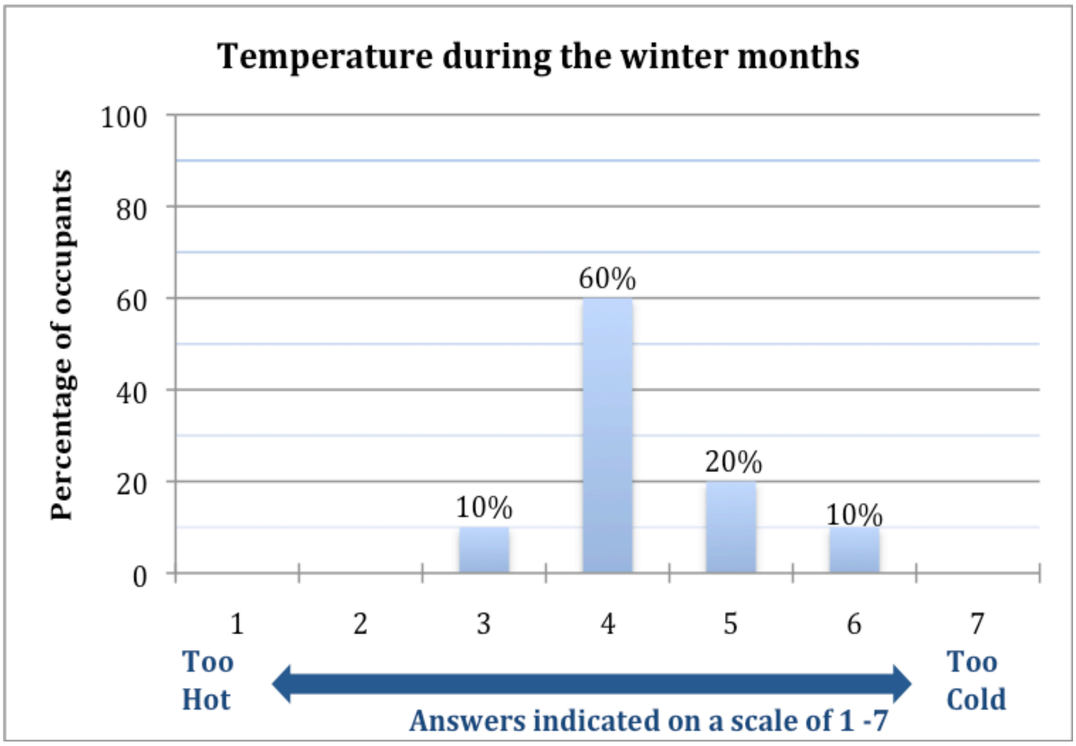


Graph 7.3. Phase 1 (Zero2020) summer temperature frequency distribution 2013 (Delaney 2014).

Note this is a summer only temperature frequency focused on overheating risk.

Thermal comfort meets the requirement for internal temperatures, which do not exceed 28°C for more than 1% of the annual occupied hours (note slightly higher in summer- Graph 7.3). High occupant satisfaction (Graph 7.4, O'Driscoll 2014)[627], good air quality and low levels of thermal discomfort (Delaney 2014) together with NZEB performance results in Phase 1 meet the aspirations of the Energy Performance in Buildings Directive, with costs in line with the final report defining the common principles of EPBD.

Delivered energy space heat demand has reduced by 90% indicating that the missed air tightness target did not have a significant impact on heat loss. Uncontrolled heat loss through passive ventilation grilles did not adversely affect the overall space heat demand. Further electrical savings could be achieved by targeting the estimated 36.8% electrical vampire and parasitic loads (Graph 7.13). Electrical demand savings were more modest at 50%, resulting in part from the lack of daylight sensors, vampire/phantom loads[25], user issues with proximity control switching and an increased utility/occupancy of the spaces post retrofit.



Graph 7.4 Occupant thermal comfort for Phase 1 (O'Driscoll 2013).

[25] Phantom load is the electricity consumed by an appliance or electrical device when it is not actively being used or is in the "off" mode. Vampire loads are associated with electricity consumed outside unoccupied hours.

7.7 A synopsis of Phase 2

As the phase 1 project was completing, the Client decided to retrofit the ground floor of Block B (immediately below the Zero2020 project). Phase 1 of the Zero2020 project, which including a large amount of research instrumentation and a BMS, had cost €473,045.93 or €1892/m^2 (including instrumentation and excluding design team fees).

The client appointed the same design team (excluding the engineers who had been responsible for performance validation in Phase 1), to execute the second stage, ensuring a level of continuity. Research team supports were removed from this project process. No additional simulation was carried out for this second project, despite changes in the design scheme. The design team, directed by the client to reduce costs, carried out a value-engineering exercise.

The client accepted proposed value-engineered changes to the *Phase 1* solution, without any performance assessment to include the following 10 variations:

1. The same façade treatment,
2. The triple-glazed window specification,
3. Excluded interstitial blinds (no replacement shading),
4. Excluded the expansion of the new ASHP or new radiators (leaving the existing uncontrolled space heating circulation system and radiant panels retained for the retrofitted space),
5. Excluded TRVs,
6. Excluded all internal works (except for remedial works around windows),
7. No air-tightness works,
8. Altered all vents to make them single, vertical and manually operated (without automation).
9. Excluded all sensors and connection to existing BMS.
10. Internal roller blinds were used instead of interstitial or glare-control blinds.

Cost comparison

The cost of the Phase 2 (the ground floor, which excluded the roof, so is not directly comparable to Phase 1) was €121,240.60 or €455/m^2 (Brennan 2013)[628] compared to €473,045.93, or €1892/m^2, for Phase 1. Note the façade was half the area of the Zero2020 project and no roof interventions were involved.

Although the researchers were not involved, they highlighted to the client the risks with the de-automation of the natural ventilation system, coupled with a super-insulated envelope, an uncontrolled heating system and a lack of integrated shading devices (other than Low-E Glazing). The design solution would meet and well exceed statutory retrofit-building elemental standards (Part L 2002 and Part L 2008); however, the resultant interior environment was indicatively (from observation and user reporting) intolerable for occupants. The super-insulated envelope retained the heat, but the uncontrolled radiators kept delivering more heat to the spaces, despite concurrent high occupancy, transpiration and solar heat gain. Occupants attempted to keep vent louvers open all the time to lower the internal temperature (this is a daily observed occurrence, even in Winter). The project, which began in June 2012, completed in September 2012. There was no commissioning process, no performance validation or post occupancy evaluation by the design team. Weekly design team meetings ended before the completion of the building and there is no evidence of a snagging or commissioning process.

In 2013/14, a separate and unconnected new build project, the *CREATE* Building, of the same scale, use and orientation, was built beside the Zero2020 project, meeting Part L 2008 for new build, at a cost of €2400/m^2 with a lifespan of 40 years.

7.8 Phase 1: Mapping Decision-making

7.8.1 Method for Qualitative Analysis

Content analysis frames the decision-making in the case studies and may support or amend the proposed **'Outline'** theoretical Socio-Technical System for Deep Retrofit. Primary data collection instruments for qualitative analysis including e-mail communications, field notes, project meeting minutes, interviews, scope of services, reports, and questionnaires. This allows a triangulation across different data sets that help avoid the biased voice of a single stakeholder, as the content analysis is drawn from a large data set of communications, field notes, minutes and interviews from the Phase 1 and Phase 2 projects (Milstein & MacQueen, 1999)[629].

Open coding was carried out using MAXQDA, which Richards and Richards (1991)[630] argued improves the rigour and transparency of data analysis. MaxQDA also offers "keyword in context" analysis for frequency content analysis using a lexical search function. MAXQDA was used rather than NVIVO or other software as the cost of the software was accessible to the researcher and the learning curve for using the software was shorter than Nvivo. The MAXQDA software also offered the ability to manage, map and cross reference 2278 coded lines from primary data, from multiple stakeholders through eight separate cycles of coding, reducing and consolidating data and into categories that were linked into a theoretical framework.

Cycles of content analysis (Braun & Clarke 2006)[631] involves the open coding of each line of primary data, sub coding and cross coding. Notes and memos were made allowing the researcher to link codes together into groups of non-hierarchical codes with clear labels and definitions to serve as rules for inclusion of units of meaning (Maykut & Morehouse 1994)[632]. In step 3 codes were categorised, grouped, re-ordered and merged along similar categories. Step 4 involves 'Coding on' which is used to restructure each of the categories into subcategories, broadening the depth of knowledge of activities, interfaces and behaviours in each category, thus offering clearer insights to what is happening in each category. In step 5 categories were linked and reduced (Miles, Huberman, & Saldana 2014)[633] into inter-related design process themes. This involved a series of sub themes in the design process that may not have been sequential but where the inter-relationship and frequency of codes and categories highlight important aspects, conflicts and patterns within the design process. Categories and codes were interlinked and visualised through thematic maps, or simplified proximity based graph-theoretic technique (Barnett and Danowski 1992)[634] "to provide a broader, more holistic perspective" (Namey et al. 2007)[635]. Visualising coherences or connections between codes, categories and occurrences (Step 6), contributes to the emerging narrative from the case studies validating observational findings. The frequency of codes is scaled in these maps to highlight occurrence, intensity and repeated ideas (Namey et al. 2007)[636]. Each thematic map becomes a coherent topic of the design process. At Step 7 the themes are then mapped and cross-referenced to a macro process model and compared to existing theoretical process for gaps and additions. Relationships are drawn across themes to deduct evidenced based findings, which are rooted in the data. In the final phase (8) the findings from the analysis are reported.

In the relationship maps, line thickness and icon scale reflect code frequencies. The icons/graphics are scaled for visual communication purposes but do not represent the type of visual empirical scales set out by Otto Neurath's visual language (Neurath 1926)[637]. Note this is a limitation of the software although this might be possible using other tools. Each category has a number, which corresponds to the frequency of codes therein. Subcategories are linked to categories where there are co-occurring codes. For example a theme like Knowledge and Understanding may have a category called 'co-ordination'. The Co-ordination category will be subdivided into co-occurring codes in sub categories. Subcategories like 'Cost centric Decision making (10)'; 'Roof light (12)' or 'Architect (7)' groups within the subcategory illustrating the frequency of coded coordination issues arising in the case studies. Thus it becomes clear what coordination issues arise and what the patterns of relationships are.

7.8.2 Analysis of decision-making in Phase 1

As the codes started to be collated, they were categorised and sub categorised, with notes, analysis and cross-coding and then synthesised into central themes, which impact the socio-technical processes. The frequency of codes is illustrated in the developing and inter-related main themes in Figure 7.6. The highest frequency of codes arose during the design stage, and this may be reflective of a higher amount of stakeholders and communications intensity. During the design stage the key issues arose around the theme of cost and performance. Uncertainty around budgetary issues impacted the selection of ECMs for the strategic design solution, extending the design process, leading to conflicts and fracturing the narrative. The main themes arising from the analysis (figure 7.6) have systematic implications. Frequent budgetary reviews resulted in the removal of ECMs from the strategic schematic without the apparent understanding of overall project performance targets, or without an understanding or appreciation for the implications of cuts. Problems and conflicts arose which impacted frequent iterations of the scheme, causing delays and requiring performance validation of the revised scheme, which often did not happen. The implication of the cost-centric decision-making, which was a very dominant theme, raises questions of the level of knowledge and understanding (of project goals and the tacit understanding of the implications of cost cutting decisions) amongst design team members.

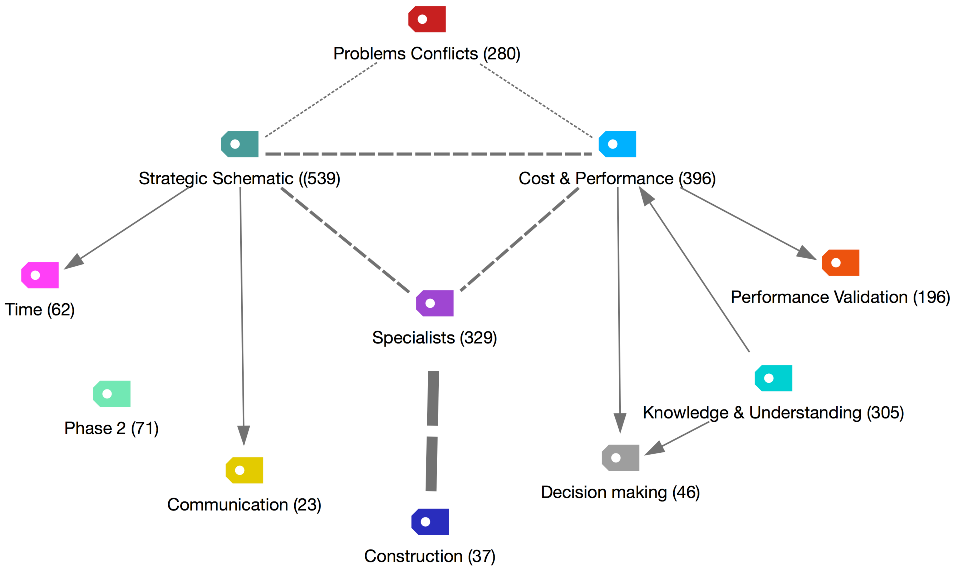


Figure 7.6: Phase 1 Qualitative Analysis Mapping Main Themes and coding frequencies (O'Riain 2016)

Although a level of economic analysis at the pre-design stage results in a budget being established for the aspirations of the project, the uncertainty of a budget dependant on unsecured incentives (grant aid) resulted in immediate rationalisation of the strategic scheme. The absence of scenario and risk analysis supported by validated performance implications at the outset of the design process, as demonstrated in case studies at Letterkenny and Dundalk in Chapter 6, resulted in 8 iterative schematic changes (Figure 7.7). Rationalisation reviews resulted in the elimination or re-instatement of ECMs, some critical to overall functionality and performance, including PV, BMS and interior wall air tightness, without performance analysis of the energy or environmental consequences. The frequency of the ECM change was very disruptive for the design process, complicating whole building performance simulation analysis and leading to conflicts. The lack of scenario analysis at pre-design or at the front end of the design process complicated the remainder of the design process leading at times to conflicts and disharmony.

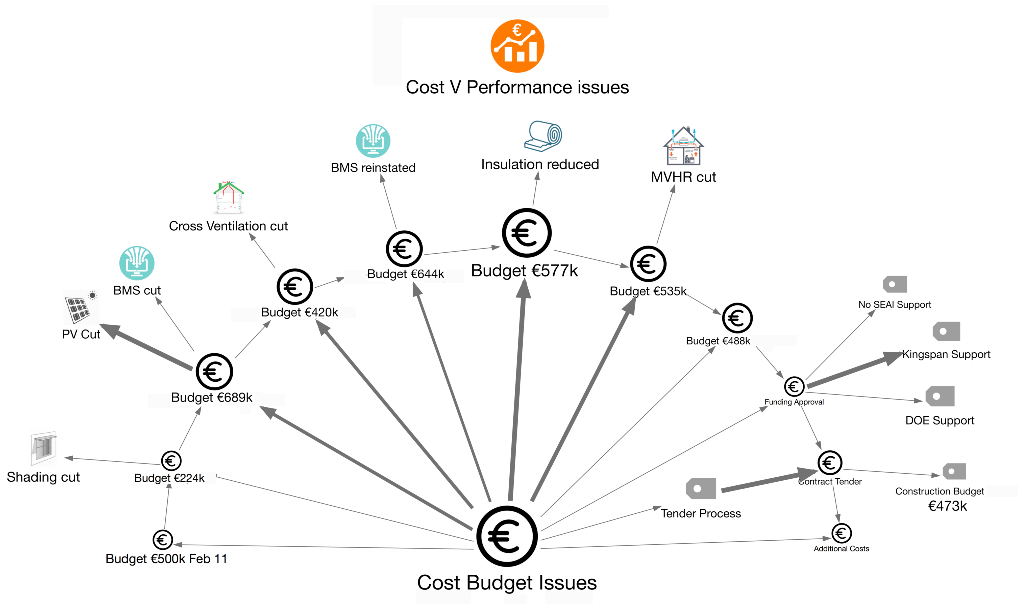


Figure 7.7: Phase 1 Qualitative Analysis of Cost issues arising during the design Process (O'Riain 2016)

On a macro level, the research team followed the theoretical 'Socio-Technical System for NZEB Retrofits', augmenting the front and back end of the design process with goal setting, establishing a baseline of existing building performance, examining precedents, creating a performance brief and simulating a target building performance, together with measurement and validation.

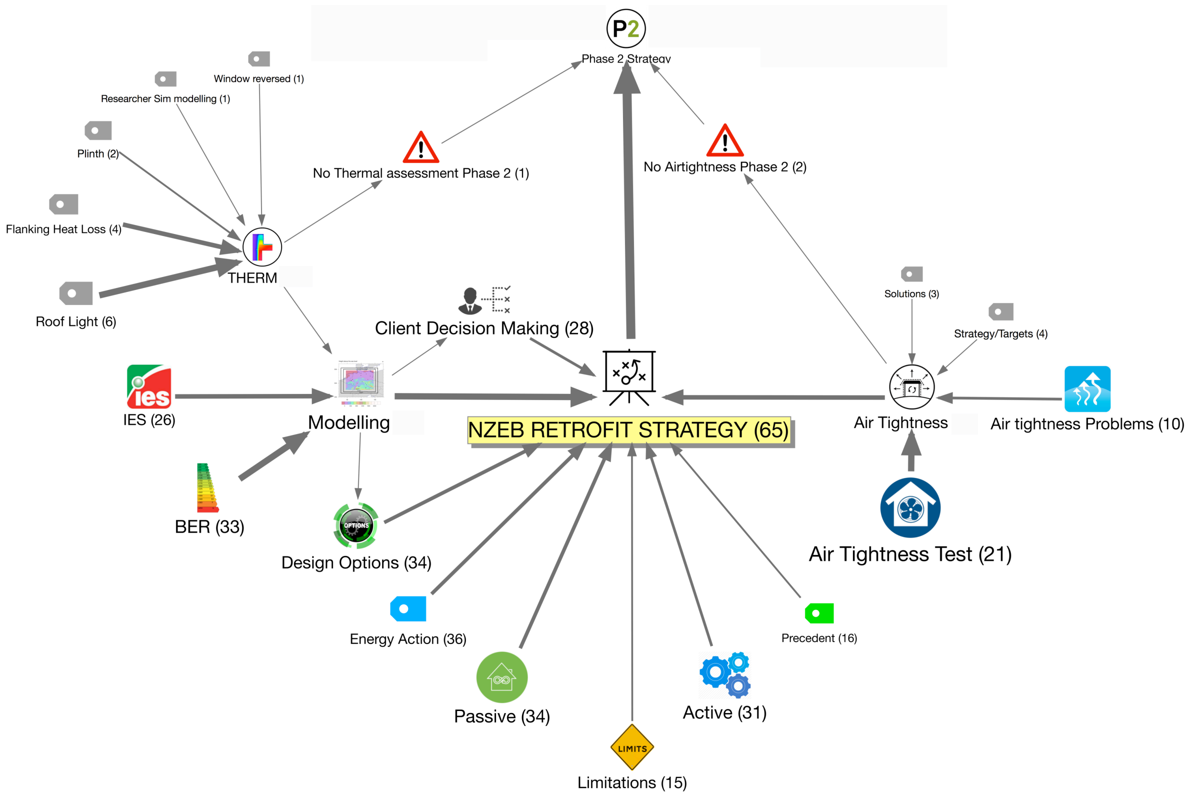


Figure 7.8: Phase 1 Qualitative Analysis Mapping of NZEB Retrofit strategy Process (O'Riain 2016)

The main themes arising from the NZEB Retrofit strategy are decision-making, thermal bridging analysis, simulation modelling of whole building performance (IES & BER), air tightness issues, passive and active ECMs.

A gap in anticipated responsibilities develops in the collective process. The thermal bridging simulation modelling of the cladding frame and windows was captured by the frame manufacturer-using Therm (for windows), under direction from the Architect. The simulation modelling of the whole building performance falls within the remit of the Engineer using IES Apache Sim. However, the thermal bridges arising from the connection of the frame to the existing structure, parapet and roof light junctions, and interstitial condensation risk are not initially captured by the design team. Neither the Architect nor the Engineer (Fig 7.8) picked up the potential risk factors of additional heat loss associated with thermal bridging, potential air tightness issues or interstitial condensation risk, each potentially impacting performance and creating design solution viability risks.

The norms and routines of the existing design process where members of the group have established characteristics, roles (Lawson 1980), engage in particular actions and have collective responsibilities (Wenger 1998) for performance (Brown & Duguid 2000) potentially embed demarcation lines. Traditionally the architect is responsible for form and envelope of the building, the engineer for its stability and services and the Quantity Surveyor for managing the budget. A performance oriented building project has a complex range of inter-dependant energy conservation measures. The whole building performance is therefore also dependant on the envelope performance, and higher potential heat loss from thermal bridging and air infiltration, whilst fabric retrofit solutions can impact condensation risk. If replicated across the industry, the demarcation gaps in responsibility found in the RTC retrofits, have the potential to impact building energy and environmental performance across a greater range of building retrofits. The issues demonstrate either a knowledge and understanding problem between these design team members or supports the contention that the existing design process is “slow to change and slow uptake of performance-driven process” (Zapata-Lancaster & Tweed 2014)[638].

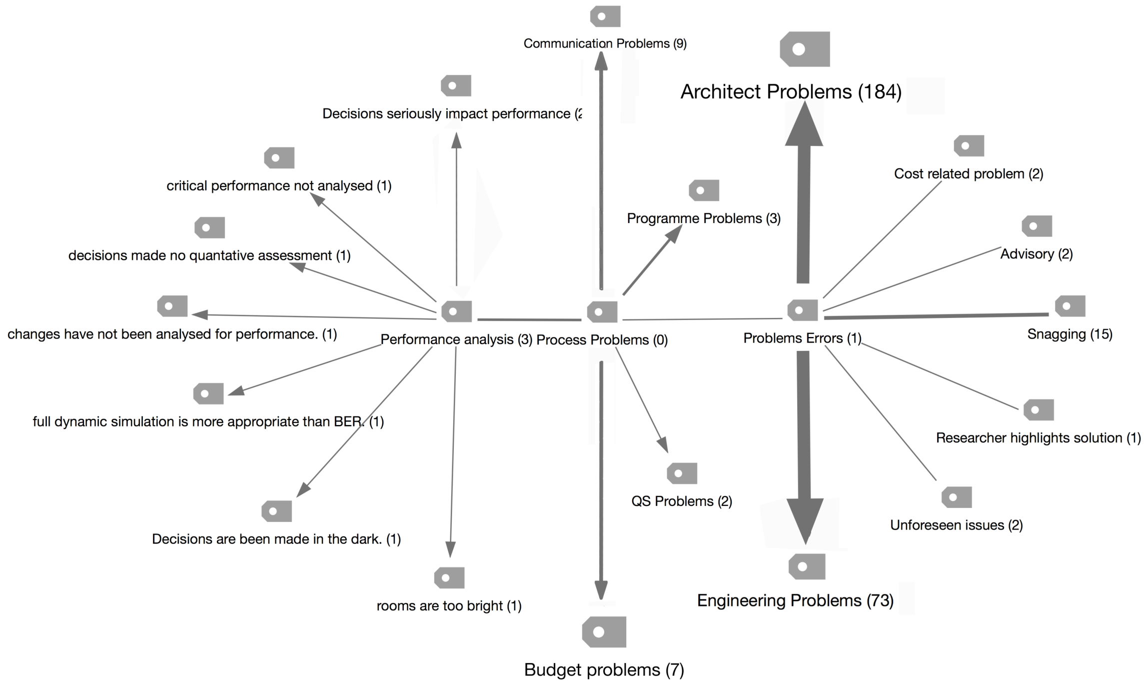


Figure 7.9: Phase 1 Qualitative Analysis Mapping of NZEB Retrofit Process Problems frequency (O'Riain 2016)

Process problems in the RTC retrofits examined in this study (Fig 7.9) may highlight the frequency of issues and problems that arise more holistically in the architects and engineers' realm. Whilst this mapping (Fig 7.9) might infer that the roles are responsible for the vast majority of problems that arise, a closer examination of disciplinary specific issues are required.

In this instance, the main problems arising in the architectural process (Fig 7.10) thematically related to thermal bridging/coordination issues leading to delays and air tightness issues impacted by knowledge/understanding issues. Specialists supported gaps in the architectural design process providing performance validation through the use of simulation tools; Therm (for thermal bridging risk) and Wufi hygroscopic analysis (for interstitial condensation risk). Air tightness problems arise both from knowledge/understanding issues and cost cutting issues. Coordination problems arise predominantly from delays from either a lack of performance analysis prior to tendering, or delays in circulating construction drawings. Conflicts arose predominantly from the lack of simulation modelling, performance analysis of envelope detailing and budgetary revisions. The lack of simulation analysis and understanding of performance consequences of detail design decision-making highlights the importance of augmenting the design process with performance reviews and BPS tool in the context of RTC retrofits, and potentially to a wider body of similar non-dwelling retrofits.

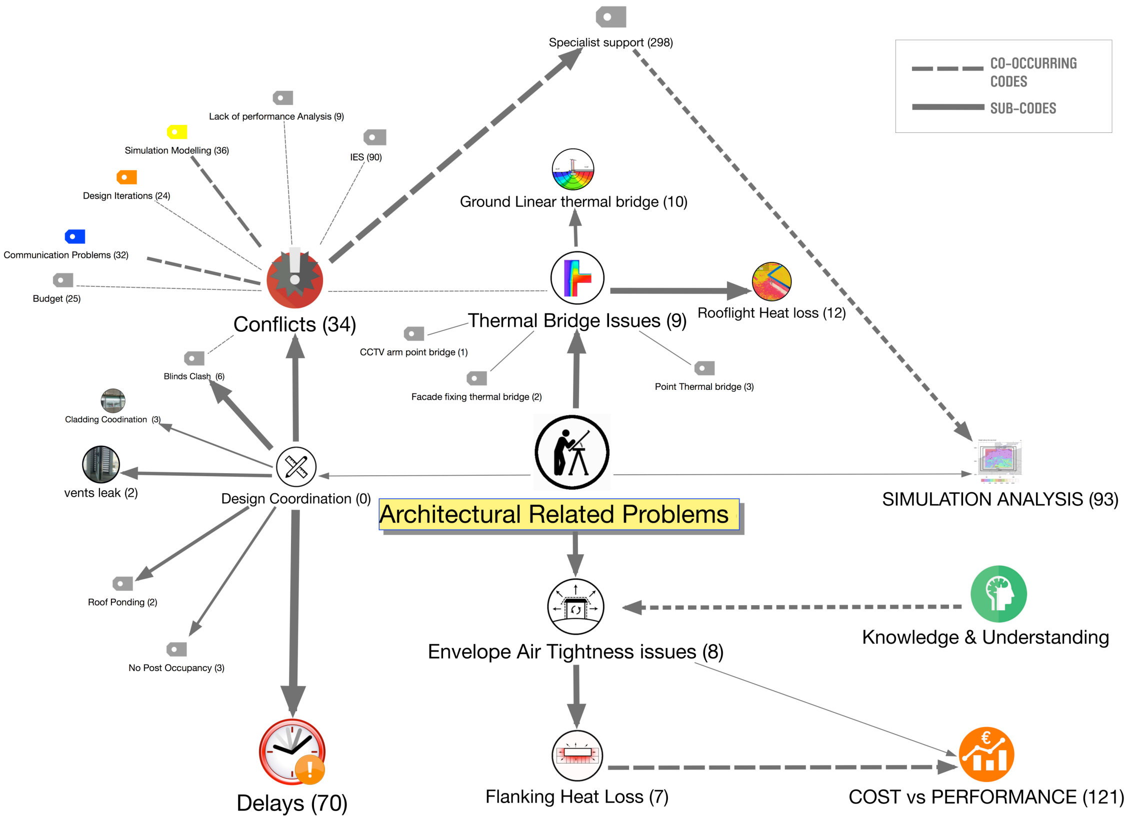


Figure 7.10: Phase 1 Qualitative Analysis Mapping of NZEB Retrofit Process Architecture related Problems frequency (O'Riain 2016)

Interstitial condensation issues do not arise in the mapping, as specialist risk analysis has clarified that the proposed build up did not need to be altered, but the decision to use an external insulation together with cavity insulation would enclose the existing concrete cladding panel, which had absorbed a high degree of moisture from driving rain over its lifespan. This potentially this could have seriously compromised the entire solution, if the egressing moisture was trapped in the construction resulting in interstitial condensation, however the Architect appears not aware of this risk.

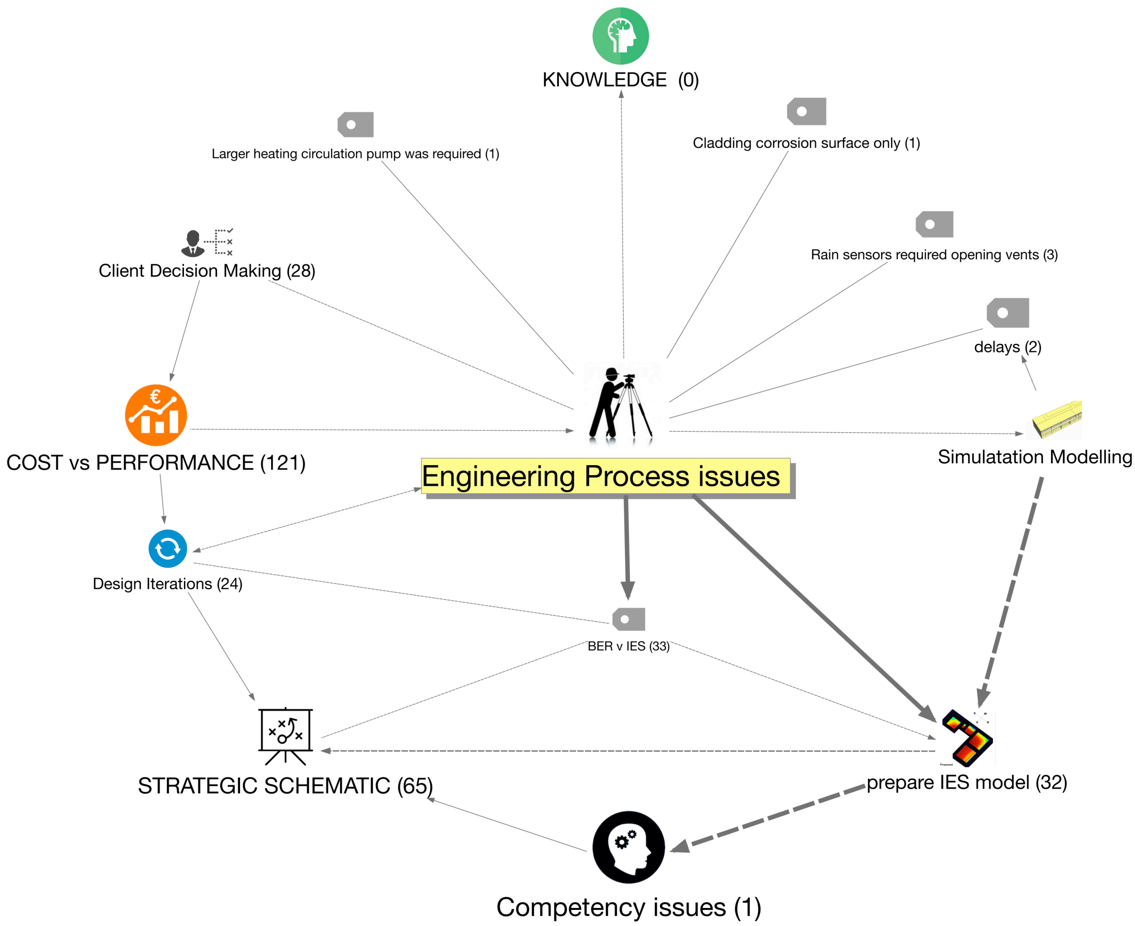


Figure 7.11: Phase 1 Qualitative Analysis Mapping of NZEB Retrofit Process Engineering related Problems frequency (O'Riain 2016)

The main problems arising in the engineering process (Fig 7.11) arise from the frequency of design iterations to the strategic schematic complicating IES modelling, which prevented validation of design iterations arising from cost revisions. A proposal to use Building Energy Rating (BER) as a performance validation methodology compounded delays. Budget uncertainty issues had a large impact on this process but may have been resolved by an early design stage scenario and risk analysis. Other issues could be related to normal design process snagging.

Specialist simulation and risk analysis together with the report by the external air tightness consultant highlighted deficiencies in the design process, which would have quantifiably impacted project goals and targets (See Appendix 7 for results). The interventions augment the design process, reducing the scope for performance risks.

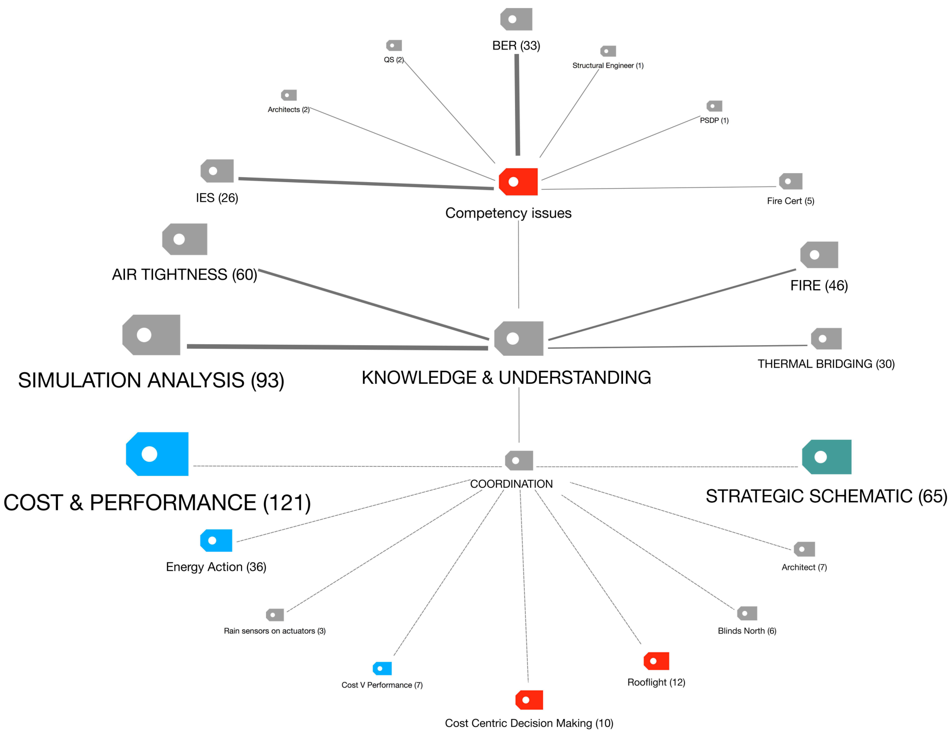


Figure 7.12: Knowledge and Understanding Thematic map of issues arising in Phase 1

The frequency of codes draws attention to key areas of concern in the knowledge and understanding of performance oriented retrofit in this design process specifically for the RTCs. Air tightness and thermal bridging are recurrent problems in the process and the need for simulation analysis. In Phase 1 fire engineering issues score highly in the absence of a fire engineer or architect at an earlier point in the process. Cost is a major factor in determining the design strategies and the lack of a scenario analysis at an early point in the process. This budgetary complication leads to a series of budget revisions illustrated in Figure 7.7. Value engineering or cost centred decision-making is made in the absence of performance analysis, creating a high risk of failure. The lack of familiarity amongst professionals with such risk issues infers deficiencies in the tacit knowledge of the design team, and particularly for the Architect in detailing for air tightness and thermal bridging, or indeed recognising the potential for interstitial condensation risk, that is particularly pronounced in this retrofit scenario.

Competency issues therefore arise both with the architectural process (fig 7.11) and the engineering process (fig 7.12). The engineer attempts to use a BER assessment, rather than an IES simulation as validation methodology, only to realise that it is not sufficient to capture all risks involved. The delays in analysis therefore impact the validation of design iterations. The tacit knowledge of the architect is insufficient to recognise potential problems with air tightness, thermal bridging and interstitial condensation.

Communication and coordination issues create less frequent issues than simulation, air tightness, thermal bridging and fire (frequency analysis previously discussed in 2.3.2). As the project moved to tender phase the design team cut specifications without communicating this to the client team, resulting in conflicts and additional costs during construction. Coordination issues with oversized blinds blocking vents demonstrate the lack of overall building performance knowledge in architectural specification and a lack of coordination between disciplines.

7.8.3 Analysis of decision-making in Phase 2

The decision by the client to reduce the budget to €455/m^2, 75% less than the performance oriented Phase 1 budget had a dominant impact of design team decision-making thereafter. With an established immediate precedent, the 10 alterations to the scheme went without any performance assessment of their impact either on energy or environmental performance. Despite warnings at the outset of the project from the research team, the design team together with the client effectively ignored the environmental consequences of combining a super-insulated envelope, with an uncontrolled heating system and a lack of solar heat gain control.

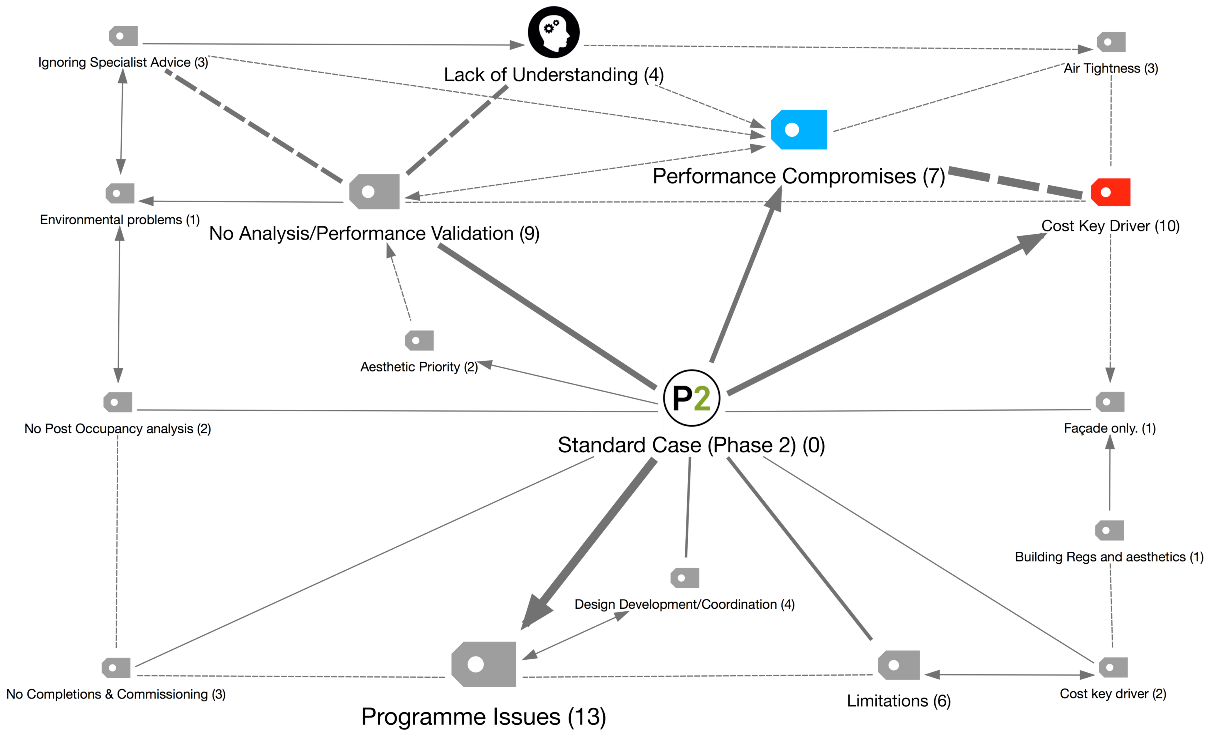
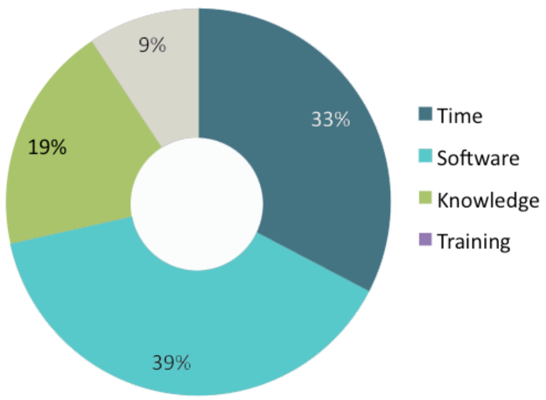


Figure 7.13: Thematic map of issues arising in Phase 2

The low level of regulatory intensity allowed client and design teams to make such decisions. There was little or no "brake to restrict the clients commercial drive" (Lawson 1980)[639]. The existing upper floor external cladding led to the decision to carry the same façade scheme to the ground floor. As the insulation far exceeded minimum regulations, the design would easily comply with TGD Part L 2002 & 2008 for retrofit. By changing the automated vents to manual vents the design would still comply with the purge ventilation of TGD Part F (2009). No air tightness measures were taken, as they were not a mandatory requirement. Despite the existence of a local Air Source Heat Pump from Phase 1, no financial provision was made to extend this to the ground floor. The client had decided not to install TRVs to the existing heating system because of a planned flushing of the system the following year.

This level of decision-making illustrates the decisive impact of budget, targets and goals on the design process in this RTC retrofit case study. If a similar level of decision-making were experienced across a broader range of retrofit typologies, then the existing low policy intensity regulations, market demand and client targets would be unlikely to result in the level of performance oriented goal setting required to meet NZEB performance and the aspirations of the EPBD 2010. The lack of validation, scenario analysis, and simulation or post occupancy may illustrate common standard practices, and by extension the challenges faced by the existing design process in shifting to a performance oriented design process. In this phase design team meetings complete prior to the completion of the project and there is no evidence of commissioning and post occupancy evaluation. Indeed the client representative was not aware of any environmental performance issues.

The extremely truncated nature of the Phase 2 design process (Figure 7.5) reduces the time commitment by the various disciplines within the design team. The competitive nature of fees and the backdrop of the recession in 2011-2012 placed an enormous pressure on a design practice’s time allocation to projects. In a questionnaire of 150 design professionals, they cited ‘Time’ as a major barrier to the use of simulation modelling as a validation method (Graph 7.5).



Graph 7.5: Questionnaire of 150 design professionals in Ireland: What are the main barriers to your practice using simulation tools to verify design detailing? (O’Riain 2015)

7.9 Synthesising Cases Study analysis

Phase 1 acted as the Deviant case where a standard design process is augmented with specialist knowledge and additional processes. Phase 2 acted as a standard case, where a design team set used established processes guided by client priorities, statutory standards and normal market forces.

In Phase 1 (Zero2020) the researchers used a voluntary standard as a basis for the performance brief following the aspirations of the EPBD Directive and nZEB standards (as known in 2012). In Phase 2, client's motivations shifted back to normal behaviour, and were primarily driven by cost, time and minimum standards.

Despite the design team's experience with the Deviant case Phase 1, which became an immediate and relevant precedent, with knowledge gained from interaction with the research team acting as energy performance specialists, client goal setting for Phase 2 became regulation and cost centric, thus shifting design team motivations away from energy and environmental performance. The Standard Case Analysis (Phase 2) for RTC retrofit illustrated that in the absence of specialist supports, energy/environmental performance targets and in the context of a low regulatory intensity, the design process became truncated. There was no use of scenario analysis and no use of building performance simulation tools, no commissioning and no post occupancy analysis.

Although engineers are capable of using building performance simulation tools (primarily IES), simulation of design iterations were too slow to inform iterative decision-making and costing exercises (in the absence of scenario analysis at an earlier point). Thus ECMs would be rationalised without reference to performance consequences. This would support the need for an external specialist to support during the design phase for ***'risk analysis/strategy review and simulation analysis'*** to ensure that the consequences of decision-making could be evaluated for energy performance in RTC retrofits, and perhaps beyond to a wider public and commercial building stock.

Engineering BPS tools were focused on building energy consumption, light, and heat gains, typically associated with sizing mechanical heating systems and ventilation. However, the simulation of thermal bridging for architectural details fell outside the demarcation of the engineer in existing design process paradigm. Thus project performances could have been compromised by the risk of heat loss through air tightness or the potential for interstitial condensation as result of enclosing the existing exterior cladding. This highlights, in the demarcation of disciplinary roles, that architects, or an external specialist is needed to evaluate design iterations for condensation risk, conductive and convective heat loss in a timely fashion to inform each design iteration and design team decision making on cost revisions.

In Phase 1 communication and understanding issues impacted decision-making and budgeting of proposals. Critical functional components of the building performance scheme were frequently removed from budget iterations, by the QS, without analysis of the impact by another team member. The addition of scenario performance, budget and risk analysis at the beginning of the design process would improve the Socio-Technical System for NZEB RTC Retrofits.

Interdisciplinary coordination errors occurred due to a lack of understanding of the inter-related nature of all design components to the overall building performance. This highlights and supports that 'knowledge and understanding' are key established barriers to NZEB performance and can be addressed through experience or training. In the short term working with specialists may offer design teams insights and a better understanding of NZEB projects.

Extended commissioning issues and an absence of post occupancy performance in phase one and a complete lack of commissioning and post occupancy in phase 2 limits learning opportunities and potentially impacts performance. The practice of architecture within the 'com*munity of practice'* of the design team, appears to end abruptly at practical completion with little interface with the project thereafter. The tacit knowledge of the research team, acting as external specialists, anticipated the problems, resolving commissioning issues, carrying out energy and environmental post occupancy analysis. In this way the loop could be closed and a report to the client could justify the investment, establish the performance and address the goals set at the outset of the design process.

A reality of the design process is the level of design team fees for the project with post occupancy concerns being limited to a 12-month defects and liability period (rather than a performance validation). Brophy & Lewis (2011)[640] highlight that most architects would expect an extra fee for this service. The time involved in providing pre-design stage planning, scenario analysis, simulation analysis, risk analysis, performance analysis, staged commissioning and post occupancy analysis is a barrier to providing these services within the existing process. Therefore, it may be far more straightforward to introduce an additional external specialist to address these issues with distinct fees for these services.

Thus, in mapping the key interactions of the design team and the priorities of the client a number of key issues arise from the analysis of the potential of the design process to achieve and EPBD NZEB retrofit performance in an Irish context in RTC buildings:

1-Client driven energy and environmental performance targets at the outset of the project are critical to motivating the design team toward NZEB retrofit performance.

2-Mandatory standards and cost are key drivers in client motivations and targets for retrofit, in the absence of convincing scenario analysis and finance models.

3-Building Performance tools used by engineers may not address fabric related heat loss issues associated with air tightness, thermal bridging and condensation risk.

4-Client side NZEB specialists can augment design team processes, strategies and tools to support NZEB retrofit building energy performance, bridging the knowledge, understanding, communications and skills gaps that exist in the design process (in RTC retrofits in Ireland).

5-The findings might infer that Irish design teams are unlikely to achieve NZEB retrofit without greater collaboration, narration, and improvisation (Brown & Duguid 2000)[641] with NZEB specialists. Deep retrofit has been shown, in the case of Phase 1 (Ch.7.7), to deliver 74% regulated final energy demand savings whilst improving environmental conditions and expanding the buildings fabric lifespan by 40 years at 80% of the cost of an equivalent new build. However, without sufficient client goals and supplemental design processes/tools, the phase 2 project demonstrated that a 'standard run' case did not achieve the aspirations of the EPBD 2010. Whilst the findings are limited to 2 case studies, the evidence from the previous case students (in chapter 6) would support that contention that improved client goal setting, regulation intensity and design team processes can improve building energy performance for retrofit.

Taking the findings from a variety of case studies over a period of time, together with the survey of design professionals may infer that the existing design process in Ireland, the capabilities, experience, knowledge, understanding and use of BPS tools to validate design energy performance by its main professions, may not be capable of delivering NZEB performance. However, together with minimum statutory NZEB standards and adopting an amended Socio-Technical System for NZEB Retrofits, augmented by the use of NZEB specialists, the design process could meet the intentions underlying the EU Directive on near zero energy buildings.

The amended version of the Socio Technical System for Deep Retrofit adds cost analysis and net present value analysis at the pre-design stage to reduce the potential for conflicts and make the selection of strategic energy conservation measures more straightforward. This can reduce design iterations and simulation performance reviews. Energy Performance contracting may be a useful method of addressing some of the capital issues allowing again for investment in strategic energy conservation measures. Detailed design simulation is added to capture the demarcation gap between the macro energy performance simulation by engineers and the micro performance validation required for envelope solutions. Sensors are added to Sub metering to allow for the post occupancy analysis of environmental conditions. Where in the majority of precedent case studies (in Chapter 6) and the phase 2 project there was no post occupancy analysis, it is clear from Phase 1 that it is very important in validating and reporting the solution's performance and justifying the initial investment. The experience gained from a closed loop where the results inform practice improvements could greatly improve design stage outcomes.

7.10 Recommendations

Addressing the research question RQ5: **"How can we adapt the design process in Ireland to meet the intentions underlying the EU Directive on near zero energy buildings?** The case studies discussed in this chapter have deducted that an augmented design process can be adopted to deliver a measured and validated NZEB building energy retrofit performance, in the context of RTC buildings. Whilst the Irish building stock has a wide variety of typologies, and the findings of this analysis may be delimited to RTC buildings, the patterns and regularity of issues arising though the case studies might induct that such a solution may be applicable in a wider typological context. The theoretical **'Outline'** Socio-Technical System for Deep Retrofit can be amended to include scenario analysis at the beginning of the design process stage and external specialists are included to support the design process (Fig 7.14).

" The fieldworker knows that he knows, not only because he's been there in the field and because of his careful verifications of hypotheses, but because "in his bones" he feels the worth of his final analysis"

Glaser and Strauss (1965)[642]

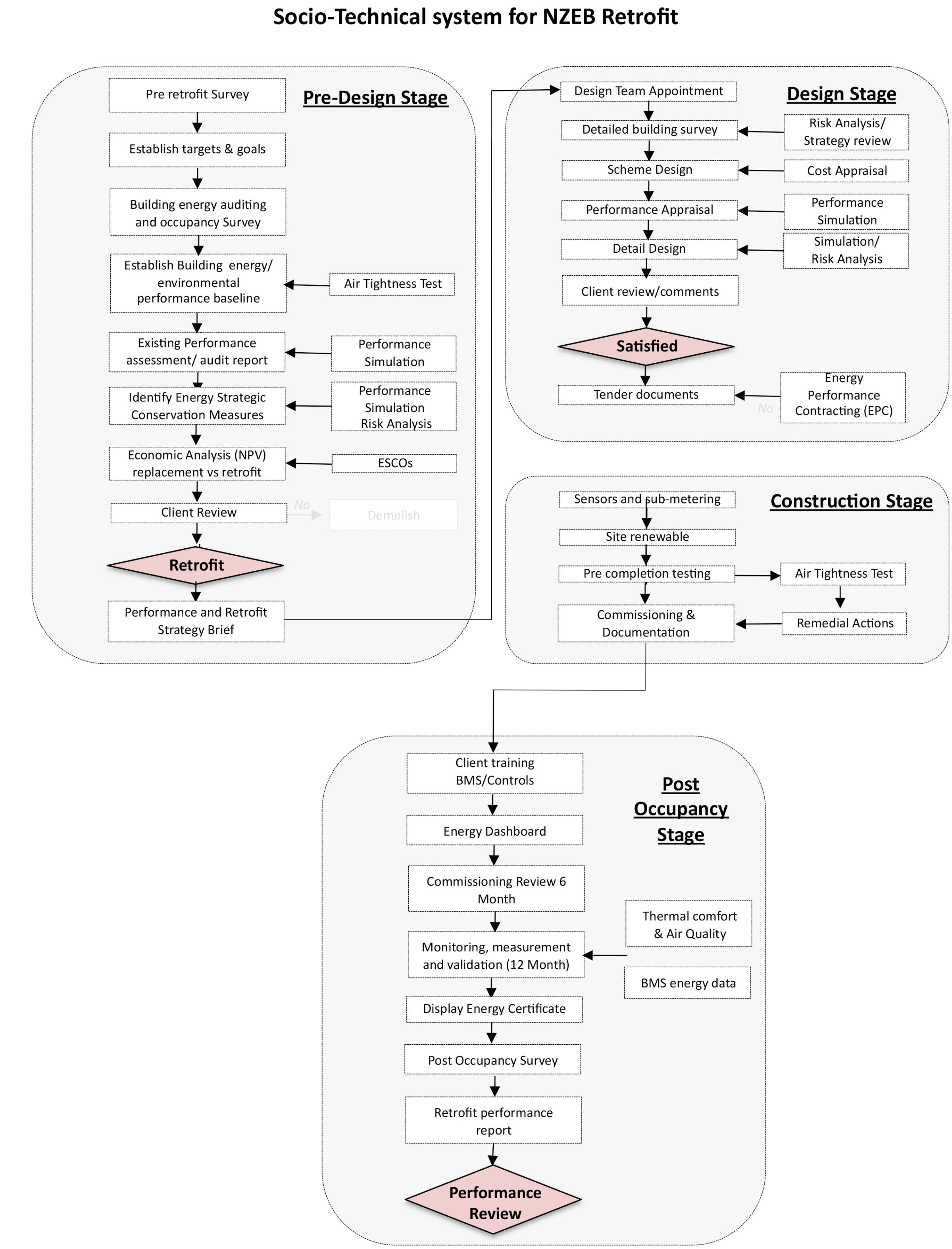


Fig. 7.14 Amended Socio-Technical System for NZEB Retrofits

(O'Riain 2016).

CHAPTER 8

FINDINGS AND DISCUSSION

Chapter 8: Findings and Discussion

8.0 Principle Findings

Even though the first "Zero Energy Building" was constructed in 1975 in Copenhagen (4.4.1), there were no nearly or Net or zero energy building retrofits in Ireland by 2010. The EU Energy Performance in Buildings Directive (EPB 2002) was recast in 2010 (EPBD 2010) aiming to address market barriers and increase policy intensity as identified by Franunhofer (2009)[643]. The EU Directive (EPBD 2010) identifies a roadmap to mandatory *nearly Zero Energy Buildings* (nZEB)[26] performance by 2019 (public) and 2021 (private), for new and retrofitted buildings (over 25% envelope). Ireland introduced high policy intensity regulations for new dwellings in 2011, which resulted in a 58% improvement in building energy performances (Ch. 7.2). However, no similar revision was made to building energy conservation regulations for non-dwellings (2008), leaving building retrofit regulations at a *'low policy intensity scenario'* (Ch. 5.10) (Fraunhofer and Ecofys 2010).

A low level of policy intensity for building retrofits exists with the withdrawal of retrofit energy conservation incentives, the market exit of ESCOs (financing retrofits), limited access to credit and austerity government policies all further undermining market adoption of low energy building retrofits in Ireland. Since the introduction of the EPBD 2010, the impacts of the recession on domestic, industrial and construction activity, rather than government policies, has resulted in a 9% fall in GHG emissions (Ch. 5.6). The Environmental Protection Agency has warned the government it can't depend on the recession to

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[26] Nearly Zero Energy Buildings performance is achieved when the building is retrofitted to a very low level of regulated energy consumption[26], this is an nZEB building. To get to a 'Zero' energy performance the balance of the energy needs to be met optimally with site renewable energy like Photovoltaic's or Wind for example, then the building can be classified as a Net Zero Energy Building (NZEB).

deliver on GHG emissions targets as economic activity improves, and significant policy improvements need to be made "including deep retrofit of existing building stocks" (Department of Communications Energy and Natural Resources, 2015) [644], (Ch. 5.6). Ireland is between 40-75% off its Kyoto and EU 2020 emissions reductions, and faces fines of €50m-€300m (Environmental Protection Agency, 2013)[645].

A review of the existing literature identified an array of systemic barriers (Golove 1996)[646] and knowledge gaps (Steinmüller 2008)[647] that may have retarded the adoption of Zero Energy Buildings (ZEB)[648] since Esbensen & Korsgaaard first achieved *NZEB* performance in 1975. A multiplicity of internal and external barriers is impacting the potential for the socio-technical design process to achieve Zero Energy Building performance. This research study therefore sought to analyse the entire *Political–Techno–Economic* system forces that shaped goal setting and decision-making actions within the socio-technical design process (Fig 8.1).

The purpose of the research was to establish the potential for a socio-technical design process to deliver measured nZEB retrofit performance in an Irish legislative, economic and environmental context and for these potential solutions to gain a sufficient level of market adoption to meet the aspirations of the EPBD (2010). The EU Directive introduced *nearly Zero Energy Buildings (nZEB)*, which have a very low remaining energy consumption profile (with a typical thermal primary energy of 15kWh/m^{2}a). *Net Zero Energy Buildings (NZEB)* performance is achieved when enough renewable energy is added to an nZEB building to meet the remaining energy demand. Achieving nZEB or NZEB performance is a far more complex challenge for retrofit than new build due to building typology, fixed aspect, volume, fabric deterioration and weather exposure of the existing building, which can increase risks and limit design solutions (Ch. 7.2).

Building upon existing literature the research set out to explore the various external factors that have decisive impacts on client goal setting for retrofit energy performance and the wider diffusion of nZEB building performance in Ireland. An optimal socio-technical design process was systematically mapped (through cross case comparative case study analysis) and tested against action research deviant case and standard run case projects to address the “scale and complexity” (Brown & Vergragt 2008) of the nZEB/NZEB retrofit challenge in Ireland.

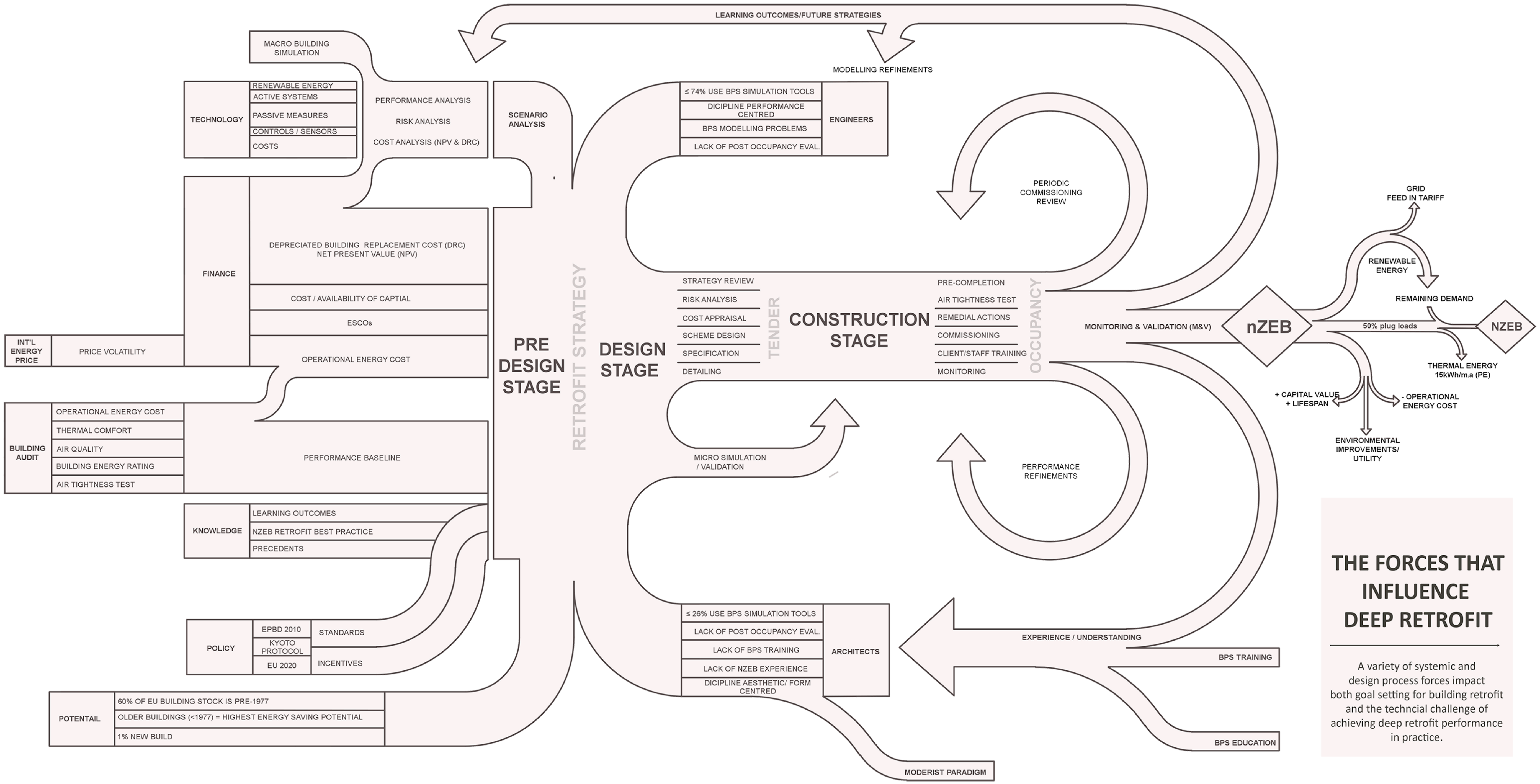

Fig. 8.1 The forces that Influence Deep Retrofit (O'Riain 2016).

8.1. Research question findings

To address the established gaps in knowledge and to identify specific barriers to nZEB adoption in Ireland, the following findings were established addressing the 5 research questions set out Ch 1.2.

8.1.1 RQ1. What were the multivariate factors that shaped the design and performance of the Regional Technical College Buildings in the 1970s?

An architectural paradigm bias towards tectonics and composition, a lack of 'relief', the limitations of the industrialized system of construction, the Irish design and construction sector's lack of experience with this system, cost cutting, time and political interference were the major factors that influenced the design and construction of the Regional Technical College Buildings in the 1970s. Before the advent of the first international *Oil Crisis (1973/74)* there were no elective or mandatory building regulations in Ireland, with no requirement for envelope insulation standards, resulting in poor thermal energy performance of the realised buildings, which were built predominantly without façade insulation (Ch. 3.2). The 'CLASP' steel frame construction system, which had been developed for fast and modular construction of post war schools in the UK, had been extensively replaced with a cheaper concrete frame system by the late 1950s (Ch. 3.3). The UK's Department of Education understood the centralised purchasing and fabrication of building parts from the Hertfordshire and CLASP building programs and had refined its budgetary guidelines to harness the benefits of centralised procurement (Ch. 3.3). This procurement system informed the structural design of the Mining and Metallurgy Building at the University of Birmingham (1965) and Loughborough University (1966) both by ARUP Associates, which became the direct precedents for the internal structural design adapted for the RTC buildings in 1967 (Ch. 3.5). Confined by time and budget, the resulting design for the RTCs in 1967 lacked the refinement, composition, environmental principles and material quality of its immediate precedents at Birmingham and Loughborough (also by Arup Associates). A post occupancy audit of the RTC buildings by the World Bank in 1980 found "serious fault with all building designs in the [RTC] project" with particular respect to the high-energy consumption and "inadequate cost provision to meet environmental (heating and ventilating) engineering needs" (Ch. 3.10).

The modular construction of the RTC buildings is now over 40 years old. They suffer from fabric deterioration with signs of expansive spalling and concrete corrosion of the aggregate panel reinforcement steel /steel fixings to columns (Appendix 6) at a number of sites where maintenance regimes failed to arrest moisture ingress. Despite this, concrete frames are more suited to retrofit than steel frame (CLASP) counterparts due to the lack of corrosion (Ch. 3.11).

8.1.2 RQ2. What are the multivariate factors that have led to Ireland's low regulatory policy intensity for retrofit building energy performance?

Although a number of seminal writers created an environmental dialogue in the 1960s and early 1970s, exogenous events such as the oil crises of 1973 and 1979, *'Cold War'* politics (1980s), the *'Stardust'* fire (1981) and *'Chernobyl'* disaster (1986) were the predominant factors that motivated government energy policies up to 1997. Although the Irish Planning Act was enacted in 1963, elective building energy regulations (1976) were only introduced in the aftermath of first oil crisis (1973/74) following policies agreed with the newly formed International Energy Agency (1974) in Washington in February 1974 (Ch. 4.5.2). The second oil crisis (1979) saw the introduction of energy conservation incentives promoting better voluntary standards for dwellings and resulting in attic retrofits to 10% of the total dwellings in Ireland (Ch. 4.5.1).

A shift in US/UK political priorities in 1979/1980 toward energy independence through oil and gas exploration resulted in falling oil prices, which undermined emerging renewable technologies and market demand for low-energy buildings (Ch. 4.10). This created a climate of public opinion unsympathetic to the idea of mandatory restrictions on the use of energy (Ch. 4, p119). Energy conservation, simple payback periods, developed for '*Twin Rivers'* retrofits (1979) and '*Home World'* (1981) low energy buildings, were undermined by falling oil prices (Ch. 4.10). A nightclub fire in 1981 in Ireland would become the seminal event resulting in the political motivation for the introduction of statutory building regulations in 1991, which effectively transposed elective energy conservation standards into mandatory requirements.

The geo-political paradigm shift caused by the '*Chernobyl'* disaster (1986) shifted *Cold War* politics towards a dialogue over the trans-national nature of environmental pollution (Ch. 4.10) bringing an international focus on environmental issues. The first UN Earth Summit (1992) and Second Assessment Report (SAR), which followed in 1995, established the potential importance of energy conservation through retrofit to mitigate global warming (Ch. 4.8). The SAR report cited the potential of Passive House (1988) methodologies to deliver 40% energy reduction (Ch. 4.4). The subsequent signing of the Kyoto Protocol (1997/98) became the impetus for the introduction of the EU Energy Performance of Buildings Directive (2002) and its recast in 2010, placing a greater emphasis on building energy conservation targets for national member state regulations. Irish standards for dwelling energy conservation were steadily increased to a high policy intensity scenario up to 2011, and Building Energy Ratings (BER) were introduced in 2005 (Ch. 4.09). Non-dwelling retrofit regulations have not been improved since the introduction of EPB (2002) or EPBD (2010) leaving Ireland with a low intensity policy scenario for non-dwellings. Whilst Ireland has adopted and transposed definitions of nZEB and carried out cost optimal calculations (2013 & 2015) for the introduction of new standards (proposed for 2017), existing building retrofit standards for non-dwellings remain almost the same as 1976 standards. By contrast dwelling energy standards reflect a high policy intensity scenario, and has resulted in "94% of properties built in last 6 years awarded A or B [energy performance] rating…[compared to] 36% of dwellings constructed during 2005-2009" (Central Statistics Office, 2016)[dcxlix] (Ch. 7.2).

Case study research of RTC retrofits has illustrated that a low level of retrofit regulations, or a low policy intensity scenario, can undermine better energy goal setting for clients, as there is effectively no 'brake' to their commercial drive (Ch. 7.2). This in turn impacts the potential for the adoption of energy conservation measures and decision-making within the design process, in line with EPBD standards. A poor level of retrofit performance goal setting can restrict design team decision-making from adopting and applying ECMs. This in turn results in a low level of market adoption of deep retrofit in Ireland. With a lack of exemplars and survey findings highlighting a low level of experience, knowledge and understanding in the application of low energy retrofits, the Irish socio-technical design process faces a number of systemic and design practice barriers to achieving nZEB or NZEB performance (Fig. 8.2).

8.1.3 RQ3. Will the transposition of the EPBD directive result in 'high policy intensity' scenario for building energy retrofit regulations?

The Irish government's retrofit policy diffusion sees it only achieving 10% of its intended annual dwelling retrofit target by 2020(Ch. 5.6). The EU has highlighted that Ireland is under-performing in GHG abatement targets and the EPA has warned the government that they will miss their GHG 2020 targets by a margin of 40%-75% (Ch. 5.6), and risk facing fines of €50m-€300m per annum from 2020

(Environmental Protection Agency, 2013)[dcl]. A serious change in government policy diffusion is required across a number of sectors to ameliorate this position. In the context of nZEB retrofit, market failures, a lack of revised mandatory legislation since 2002 and reducing oil prices are seriously impacting the potential for this sector to contribute to GHG abatement.

The EPB 2002 and EPBD 2010 resulted in a 60% improvement in dwelling standards in Ireland up to 2011 and the introduction of building energy ratings (2005) (Ch. 5.3.1). The increase in policy intensity resulted in a shift in building energy performances of new builds with 94% of all dwellings built during 2010-2015 being A or B rated, when compared to 36% in the period 2005-2009 (Central Statistics Office, 2016)[dcli] (Ch. 7.2). The improvements in mandatory legislative standards saw the introduction of performance oriented building design with air tightness testing and thermal bridging detailing. The traditional use of backstop values and Acceptable Construction Details (ACDs) in the socio technical design process would now “result in non-compliant buildings” (RIAI 2010)[dclii] (Ch. 5.3.1). This forced either a change in design practices or a reliance on external specialists (not involved in all stages of the design process) such as BER assessors.

There were no elemental improvements in building energy conservation standards for non-dwellings since 2002, maintaining a low level of policy intensity for building retrofit, leaving them at similar levels to draft regulation standards in 1976 (Table 5.1). It is clear that there has been historically low policy intensity towards the regulation of building retrofit in Ireland, both for the residential and non-residential sectors.

The proposed amendments to Part L 2017 will be heavily influenced by the nZEB cost-optimal calculations (Ch. 5.9). Cost-optimal calculations recommend no fabric retrofit and no changes to the retrofit elemental standards for cost optimal nZEB. This will reduce the potential for GHG emission abatement in this sector, and potentially change best practice towards services-only retrofits (mechanical and electrical systems) (Ch. 5.10). If Ireland implements the recommendations of cost optimal calculations it will develop, as Fraunhofer and Ecofys (2010) define it, a moderate technical scenario (TECH) for future retrofit regulations (Ch. 5.10) where cost effective measures may shift the selection of ECMs towards active services and away from fabric retrofit (associated with deep retrofit), thereby maintaining low elemental fabric retrofit standards. A moderate intensity retrofit (TECH) scenario is unlikely to deliver the significant increase in deep retrofits and thermal energy reductions required by the Department of Communications Energy and Natural Resources, 2015[dcliii] to close the national emissions gap by 2020 (Ch. 5.6).

Thus, in response to research question 3, the transposition of the EPBD regulations into Irish building energy regulations, with regard to retrofit applications are unlikely to result in high policy intensity scenario, as defined by Fraunhofer and Ecofys in 2010. Serious concerns have been raised in Chapter 5.9.2 regarding the Irish cost-optimal calculation methodologies. The Irish cost-optimal calculations do not use representative reference public buildings, in terms of occupancy or energy intensity, they fail to acknowledge the role of remaining whole-building lifespan at the beginning of the calculation period and they fail to make transparent the environmental consequences of retrofit packages (as required by the Cost Optimal Regulations 2012). The proposed energy conservation standards, TGD Part L 2017, is therefore likely to be driven by improved elemental service packages, rather than improved envelope performances, thus having implications for future NZEB design practice. If this were to happen, the potential for 80% GHG abatement through the retrofit of 1960s and 1970s buildings might be technically possible but would practically remain unrealized (Ch. 5.10). These research findings have informed representations to the Department of Environment and the Department of Communications, Climate Change and Environment. More specifically, a paper on the analysis of Irish cost optimal calculations[dcliv] was presented to the Head of Irish Building Standards (Sean Armstrong) at a meeting in November 2015.

The research has and continues to contribute to a series of workshops run by the Irish Green Building Council on behalf of the Department of Communications, Climate Change and Environment. The outcomes of the various workshops have been included in a 10-point plan[dclv] to inform the government's revision of the National Renovation Strategy that Ireland to be submitted in compliance with the EU Energy Efficiency Directive by April 2017. The delayed revision to Part L 2017 for buildings other than dwelling is due for public consultation in December 2016. The research will also contribute to a formal submission to this process. The research has become very topical and immediately relevant to National policies for NZEB retrofit implementation.

Fig. 8.2 Declaration in 10 Points for a better national renovation strategy and effective implementation plan (IGBC 2016)

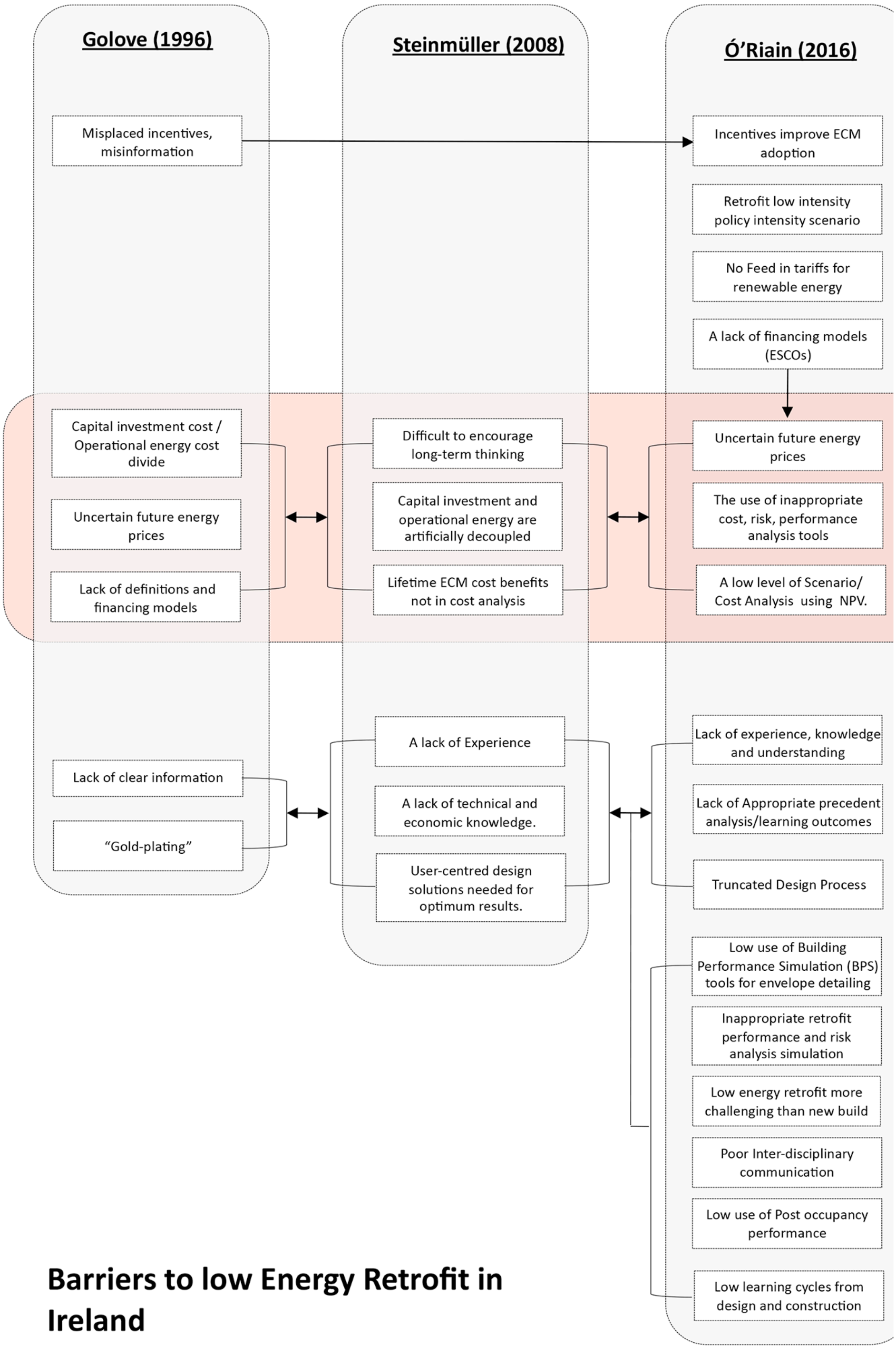

Fig. 8.3 Barriers to low energy retrofit in Ireland

Adopted from Golove (1996) & Steinmuller (2008) (Ch. 1.1.5, 1.1.9)

8.1.4 RQ4. Can precast concrete RTC buildings, in Ireland, be retrofitted using a natural ventilation strategy to achieve a measured NZEB performance?

A pilot-project (Zero2020 Phase 1) with an augmented socio-technical design process (Fig 8.3) was carried out in 2012, at the Cork Institute of Technology (formerly Cork RTC) retrofitted 1% of the existing 1974 building stock using an external insulation, high performance glazing, natural ventilation, automated louvers, low temperature radiators, an air source heat pump, low energy lighting and sensors whilst harnessing the existing internal thermal mass to moderate overheating. Monitored and validated over the calendar year 2013, the project delivered a measured primary energy performance of 85.5kWh/m^{2}a (Table 7.5), for fixed regulated loads (non plug loads) resulting in a nearly Zero Energy Building Performance (nZEB). This performance is significantly better than the projected performance of 124 kWh/m^{2}a included in cost optimal nZEB calculations (Ch. 5.9.1).

The remaining energy demand was met by a photovoltaic (PV) array of solar panels mounted on the roof offsetting the total remaining regulated and unregulated electrical demand (Appendix 7) resulting in a Net Zero Energy Building Performance (NZEB). Unregulated loads increased from 30% to 50% of annual delivered energy in this nZEB building. The greatest savings were made in thermal energy (Ch. 7.6) with total nZEB energy savings of 74% over pre-retrofit performance. This pilot project establishes the first measured nZEB and NZEB building retrofit performances in Ireland (for a non-dwelling). The project illustrates that nZEB performance can be achieved using a natural ventilation strategy rather than a forced air solution making it very suitable for education applications in Ireland, whilst maintaining air quality and thermal comfort within CIBSE guidelines. However the pilot project also highlighted gaps in the traditional socio technical design process, within the context of RTC retrofits, which would impact the potential for practice to replicate these results without significantly improved systematic and practice processes and/or specialist support. The subsequent Phase 2 project, acting as a standard case design process, demonstrated the truncated nature of the existing design process, the importance of client goal setting to the design-process, decision-making and eventual building performance. It is possible to retrofit precast concrete RTC buildings, in Ireland, using a natural ventilation strategy to achieve a measured nZEB and NZEB performance.

8.1.5 RQ5. How can we adapt the design process in Ireland to meet the intentions underlying the EU Directive on near zero energy buildings?

Comparative case studies demonstrated that socio-technical process for nZEB retrofits is open to a wide variety of inputs. External factors include the cost of energy at the pre-design stage, the availability of capital, energy conservation incentives (carrots) and mandatory regulations (sticks). Internal factors include the structure and deliverables of the design teams, experience, knowledge and understanding of low energy buildings, communications within design teams, and their technical competence in validating the energy performance outcomes of ECM selection and envelope detailing. Client goal-setting at the pre-design stage is critical to design team decision making, ECM selection and overall retrofit performance. Case study levels of client investment for building retrofit were shown to be 42% of new build (CIT 2011 retrofit masterplan budgeted €1000/m^2 vs 'CREATE' New Building at CIT in 2013 which cost €2400/m^2, Ch. 7.6). In reality investment levels for building retrofit could be much less (€455/m^2 for CIT Phase 2 or 19% of new build costs). The AUDE (2008) report on the Birmingham M&M Building retrofit (Ch. 7.6) had established that a more appropriate target for low energy retrofit would be 80% of new build. The Phase 1 project came in at €1892/m^2

or 79% of an equivalent new build cost (CREATE building 2013, CIT)[27] without efficiencies of scale. The Phase 2 project (at €455/m^2 or 19% of new build investment levels) demonstrates that existing regulations allow the market to reduce levels of investment for building energy retrofit. Investment levels can directly impact the options and energy conservation measures available to the design team and the potential for better building energy and environmental performances. Therefore, the existing low intensity building energy retrofit regulations, in this instance, can undermine client goal setting and the potential to achieve NZEB performance.

Together with external factors, the truncated nature of the existing socio-technical design process can limit the aspirations of the client in performance goal setting. Case study analysis demonstrated an improved level of goal setting occurred where design teams adopted scenario analysis; including cost, performance and risk analysis. Where there was absence of scenario analysis combined with low policy intensity for building energy conservation, a client's motivations/priorities can shift project goals to become aesthetic or cost centric.

The lack of scenario analysis informing a pre-design stage ECM strategy was shown, in a Phase 1 pilot project, to extend the number of design iterations, complicating simulation validation, leading to communication problems and conflicts during the design-process.

Design process improvements in the use, and application of energy performance simulation for low energy retrofit, is required to address

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[27] *The cost of the Phase 2 (the ground floor, which excluded the roof, so is not directly comparable to Phase 1) was €121,240.60 or €455/m^2 (Brennan 2013)[27] compared to €473,045.93, or €1892/m^2, for Phase 1. Note the façade was half the area of the Zero2020 project and no roof interventions were involved.*

demarcation issues between the engineer and the architect, in macro building performance simulation and validated design detailing. A survey of 150 design process professionals in Ireland highlighted a low use of building performance simulation (BPS) tools by architects (26%) supporting findings by Attia (2009)[dclvi] of the disparity in the use of BPS tools between architects and engineers. The majority of architectural praxis is not equipped with the toolsets to respond to the EPBD targets for nZEB performance, either through new build or retrofit, supported by the fact that 60% of architect's report this to be the case in a design profession survey (Ch. 5); findings from Pan and Garston (2012) and Hamedani and Smith (2015)[dclvii] have established that there is a low level of BPS use in practice and a need for a greater level of education and training.

Most RTC case study design processes did not include pre-design or post occupancy evaluation stages, which have been demonstrated to improve performance outcomes in the case study retrofits (Ch 6). The key factors influencing goal setting/decision making of the client and design teams were mapped and contributed to a model for an *'Outline Socio-Technical System Deep Retrofit'* (Fig 6.9).

Informed by a literature review and building on sustainable retrofit processes developed by Ma et al (2012) and others, the *Socio-Technical system for performance oriented Retrofit* was tested within a pilot project, and compared to a 'standard run' control case retrofit. Findings from the comparative analysis of this testing, contributed to amendments to the 'optimal' process, resulting in a proposed *Socio-Technical system for NZEB Retrofit* (Fig 8.2).

To achieve a greater adoption of NZEB building energy performance through deep retrofit, the design process needs to be augmented by better building energy regulations to drive client goal setting. The changes in Part L 2011 (for new dwellings) have demonstrated the impact of regulations in changing market behaviour toward better building energy performance. Without better regulations and investment levels, design teams will be limited in the application of energy conservation measures.

Scenario analysis at the pre-design stage has been demonstrated, in a number of case study buildings, to improve client goal setting beyond the minimums of building regulations and the lack of scenario analysis can extend design iterations, complicating simulation and performance validation. The use of scenario analysis at the outset of the project (in case study buildings) can clarify investment levels, energy conservation measures and streamline design stage decision-making.

Scenario analysis, which was shown in case studies to be used more by engineers, was predominantly focused on macro building performances rather than architectural detailing. Architects or NZEB specialists are needed to validate building envelope design detailing with Building Performance Simulation tools. However Architects appear (in the questionnaire-Ch 5.6 and other papers-Attia 2009) to be poorly placed to respond to such BPS tool use without further training. Changes to undergraduate Architecture courses should be made to include the understanding and use of such BPS tools. Continued Professional Development (CPD) training could begin to address such training in the professional sphere.

All but two of the case studies (O'Fiaich College & CIT Phase 1)

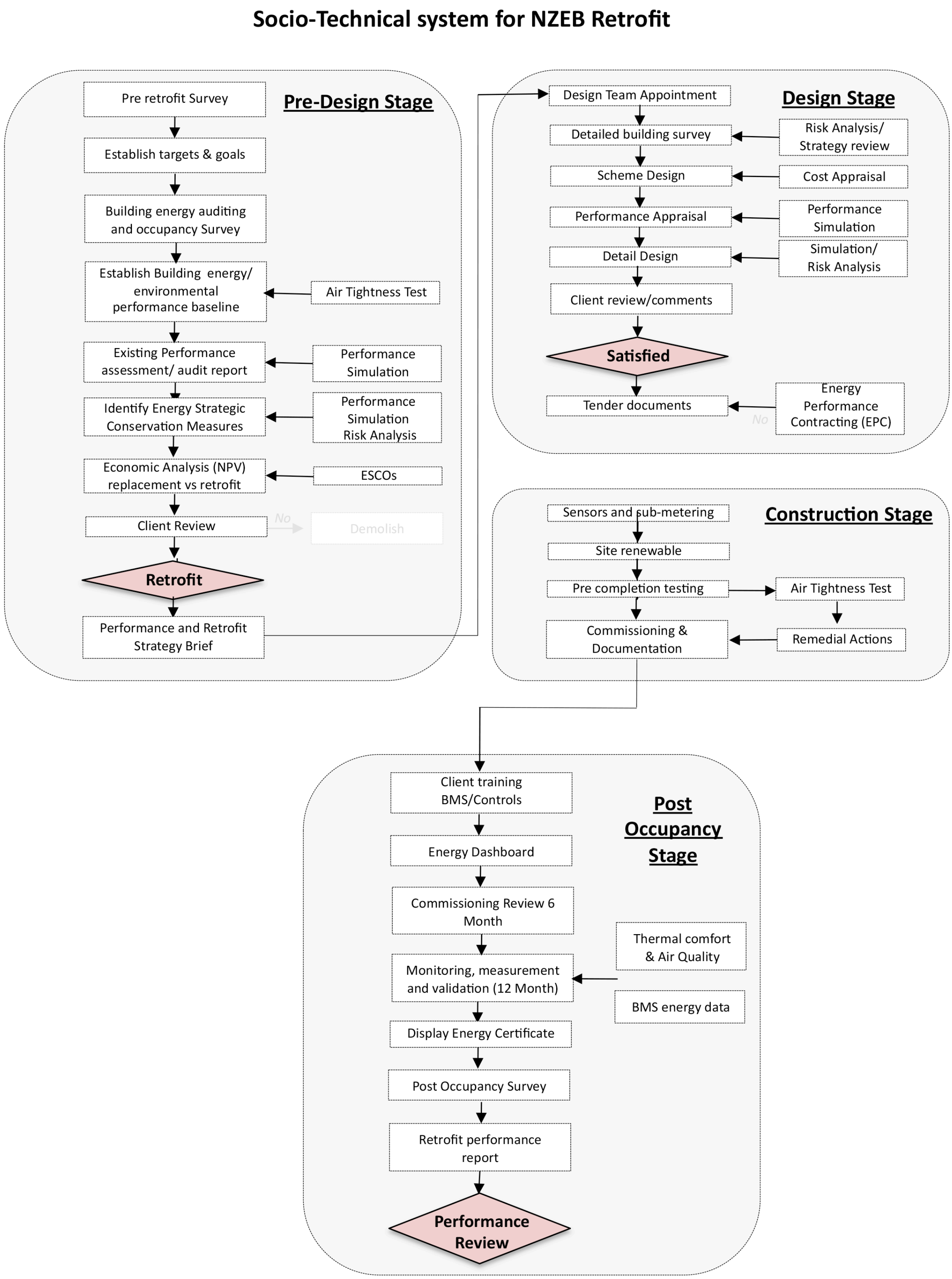

Fig. 8.2 Socio-Technical System for NZEB Retrofits (O'Riain 2016, adapting and developing from Ma el al 2012).

8.2 Interpretation

A large body of primary research, case study analysis, pilot project and existing literature supports the findings of this research. The study examined the systematic challenges around nZEB retrofit performance and adoption specifically in an Irish technical, economic and legislative and practice context. The following section discusses the meaning of the results.

Irish government policy toward retrofit remains low, and even though numerous reports by the Sustainable Energy Authority of Ireland (SEAI 2016)[dclviii], the Department of Communications Energy & Natural Resources (DCENR 2015)[dclix] and the Environmental Protection Agency (EPA 2014)[dclx] all highlight the importance of deep retrofit and the need for increased policy intensity. The Irish recession resulted in a collapse in retrofit incentives and the availability credit (Ch. 5.3.2), but did see an improvement in new dwelling energy conservation standards (Ch. 5.3). The lack of improvement in retrofit standards for non-dwellings since 2002 (Table 5.1), a failure of ESCOs in Ireland (Ch. 5.6), the amount of funding available to the market (Ch. 5.6), the collapse in state incentives (Graph 5.6) and the absence of grid connection for PV (Ch. 6.5.2)[dclxi] all undermine goal setting for performance oriented building retrofits in Ireland. The nZEB cost optimal calculations propose no improvements to building envelope retrofit standards, and thus the delayed changes to retrofit standards are unlikely to improve the potential for a greater level of deep retrofits in Ireland. Thus Ireland is set to miss its GHG emissions targets by 40-70% resulting in €50m-€300m annually (Environmental Protection Agency, 2013)[dclxii].

Policy barriers (Fig 8.1) to nZEB retrofit have a controlling impact on design stage decision-making, as they limit the extent of client performance goals, and thereby the level of ECMs applicable through retrofit. Case studies demonstrated that all retrofits from 2002 sought to exceed the minimum standards, and where scenario analysis was employed, clients were more likely to set increasingly aggressive performance goals. Some case study projects with the most aggressive standards (Dundalk 2005 and Cork Master-plan 2012) did not receive financial support and did not progress to design stage, thus demonstrating the fundamental importance of economics and financing to enable the socio-technical process for nZEB retrofit. To improve the quantum of building stock deep retrofits, funding structures for the retrofit of public buildings needs to be revised and be comparative with capital funding for new buildings. Government procurement practices (Department of Finance Multi Criteria Analysis) needs to acknowledge energy consumption as part of the decision making process. The capital investment bias toward new build also needs to be addressed. The Economist Intelligence Unit (2013)[dclxiii] argued that a client should view existing building portfolios in terms of asset depreciation, net present value (Ch. 5.9.1) and depreciated replacement cost (Ch. 7.6), where investment in deep retrofit becomes a method to lower depreciation risk. The Royal Institution Of Chartered Surveyors (2013)[dclxiv] reported that Deep Retrofit could save between 50%-80% in final energy demand whilst "create[ing] enhanced benefits in existing buildings in the form of increased productivity; increased property and asset values, carbon emissions reductions, and increased employment opportunities", whilst standard renovations only delivered 20%-30% operational energy savings and failed to add capital value. To increase deep retrofit client investment decision-making needs to switch from simple payback methods, which can bias toward light retrofit (Ch. 7.3) and shift toward fabric renewal, building lifespan and depreciation risk analysis (Ch. 5.9.1). Tools may be needed to demonstrate the impact of goal setting and ECM selection on the building value chain.

Case studies carried out as part of this research, and in particular, the pilot project (phase 1), demonstrated that challenges exist for the architect and engineer in achieving the nZEB performance.

Demarcation issues arising between macro strategies and micro simulation of building retrofit design, lead to performance problems, because architects are not adopting building performance simulation tools (BPS) as Attia (2009) had reported. De Wilde & Van Der Voorden (2004)[dclxv] found that architects did not analyse the impact of energy conservation measures, and did not carry out scenario analysis with design variants (Ch. 5.3.2).

Failure to use scenario analysis to establish risk, investment cost and retrofit strategies at a pre-design stage extended the design process, leading to conflicts, communication and coordination problems (Ch. 7.6), as Lewis (2004) had suggested might be the case in existing practice (Ch. 5.5). Engineers were wholly responsible for BPS simulation in the case study projects covered in this research, with no BPS tools used by any architects. Indeed, this research study surveys highlighted that engineers in Ireland were three times more likely to use BPS tools than architects in Ireland (Graph 5.2). Kanters, Horvat & Dubois (2014)[dclxvi] highlighted the need for more accessible BPS tools to assess the potential impact of design variants on energy efficiency and renewable production.

Architects need to be careful that they do not lose market share to engineers in an energy retrofit market that will increase by 40% in the coming decade (Navigant Research, 2016)[dclxvii]. The American Institute of Architects (2013)[dclxviii] established that the area of buildings retrofitted in the US each year was equivalent to new build, but that it was energy efficient retrofit was a "less mature practice area for architects". EU pressure to improve retrofit regulatory intensity toward 2030 is likely to increase the deep retrofit market (The Economist Intelligence Unit, 2013)[dclxix]. The lack of BPS use and experience with performance-oriented retrofits could be a particular weakness in Irish architectural practice. Whilst building simulation tools are taught to Architectural Technologists in programmes across Ireland, there is a lack of building retrofit strategies and building simulation tool modules at an undergraduate level for architects in Ireland (Ch. 6.6.8). This may limit the Architects ability to respond strategically to the design intervention required at an early stage of the project and this limit the development of future architectural practice in the deep retrofit market.

The literature reviewed over the course of this paper shows that much has been written about low energy design in buildings and the aspirations of the EPBD (2010), and yet a great variety of barriers still exist to their market adoption. A variety of approaches have been taken in existing literature to the socio technical process of deep retrofit but much of the work reviewed was based on simulations rather than built, measured and validated performances. There was a need to bring frameworks, proposed in literature, together with learning outcomes from case studies and validated through pilot projects, to inform a detailed strategic process that could improve the performance outcomes of the existing socio technical design process. King (2012)[dclxx] had highlighted the need for a consistent design team framework to deliver on the aspirations of carbon reductions, embodied in the EPBD 2010. Therefore, an opportunity lies within the context of a future improved policy framework to extend and augment the socio-technical design process to address pre-design and post occupancy stages (Fig 8.2). In the short-term experience, understanding and knowledge gaps in architectural practice may prevent many practices from expanding their services to address these areas (Ch. 7.9). Gaining experience and knowledge from NZEB specialists would help architects develop an appreciation and skills in performance oriented retrofits. Brunsgaard et al. (2014) [dclxxi] found that the building industry has an urgent need for specialists with knowledge and experience in integrated design for NZEB buildings. On the other hand King (2012) warned that the further fragmentation of the design team responsibilities could impact the ability of the design team to coherently deliver more onerous levels of building performance.

8.3 Implications

Irish legislative standards for retrofit need to be dramatically improved to achieve the high policy intensity required in delivering greater market adoption of deep retrofits. An increased level and availability of deep retrofit incentives targeting fabric improvements are needed to make deep retrofits more economically viable. A greater level of energy building performance auditing is required to inform the financial analysis and retrofit business cases for ESCOs. Financial models are required that recognise the various benefits to retrofit in the building value chain. 'Nearly' and 'Net' Zero Energy Building retrofit performance is technically possible in Ireland where there are sufficient client motivations (regulations and incentives), the availability of capital financing and the adoption of an augmented *Socio-Technical System for NZEB Retrofits.* Nearly zero energy retrofit of RTC buildings performance has been demonstrated to deliver measured regulated energy savings of 74% over pre-retrofit performance whilst improving thermal comfort and air quality to contemporary CIBSE standards. The percentage increase in un-regulated electrical loads (plug loads) in nZEB buildings biases the selection of renewable energy solutions towards electrical demand rather than thermal energy demand.

Practice process limitations and the poor level of demand for low energy building retrofit has left practice with little experience and competence to address the challenge of nZEB buildings. Architecture, more so than engineering, suffers from a lack of quantitative analysis for ECM selection, scheme design and detailing. Where engineers tend to analyse macro aspects of building performance, the use of building simulation tools by architects in Ireland is rare, as demonstrated in the analysis of the cases studies in this research, and this reflects trends in international research (Attia 2009, Ch.5.1). The lack of BPS use by architects has been demonstrated in the CIT Phase 1

(Zero2020) project and in a survey of Irish practitioners (Graph 5.2). Whilst architects can attempt to address these issues through training, there is a lack of simulation analysis education for architects at an undergraduate level. As Trebilcock et al. (2006)[dclxxii] has identified, many scheme design decisions that impact building energy performance, are made at early points in the design process by the architect, in the absence of performance or precedent analysis. Informed decision-making requires knowledge and experience in the form of precedents, experience and training which cannot be addressed exclusively by the use of external specialists at the end of the design process. Building performance, as Ochoa & Capeluto (2008)[dclxxiii] found, depends on early and informed architectural design decisions. Without this experience, knowledge and understanding Irish architectural practices are poorly placed to respond to nZEB challenges, as the survey of Irish practitioners supports (Graph 5.5). Architects clearly see time as a critical issue which disincentives the use of simulation tools and post occupancy analysis.

There is significant additional time demand (over a traditional process) involved in the proposed socio technical design process for retrofit, a major theme that arose from the content analysis of communications on the CIT Phase 1 pilot project.

Therefore, in the short term, the use of external experts or nZEB consultants could establish new fee income areas which could be seen, from a client perspective, as bringing added value, through risk minimisation and validated post occupancy performances. This can give architects the opportunity to develop experience, understanding and exposure to the tools involved in delivering measured nZEB and NZEB performance retrofits, giving them the potential to shift practice to address this new income stream. It is critical that such an expert be involved at the pre-design stage, integrated with the design team throughout the design and post occupancy process, thus avoiding the type of 'end of pipe' solutions which Zotter (2004)[dclxxiv] had warned about. Fixing strategic performance design errors at the end of the design process can present a very challenging and expensive task.

It is possible that Ireland could address its GHG emission targets by means other than nZEB retrofit adoption. A greater level of renewable energy production could be an example of such a strategy, but as McKinsey (2009)[dclxxv] identified, 'Retrofit' is one of the most cost effective measures for carbon emission abatement.

8.4 Limitations

Parts of the research findings are based on case studies and a pilot-project; therefore, some of the performance findings are finite, and limited to that typology, within an Irish economic, legislative and climate context. Although a lot of primary information was found, some of the original stakeholders had died and some of the material in relation to specific case study buildings was not available or had been lost over a period of years. The absence of post occupancy analysis and energy auditing in many case study buildings prevented direct comparisons of post occupancy results. In the analysis of cost optimal calculations the formulae used to calculate the matrices was not made available to the researcher in 2013 or 2015, thus alternative results using different inputs could not be simulated. The pilot-project performance findings are not generally applicable to other typologies but do establish the potential to achieve nZEB or NZEB performance with an augmented design process and appropriate client motivations/incentives. Not all energy conservation measures could be implemented or tested in the pilot-project because of budget limitations. Building simulation, validated by measured post occupancy performance at the Zero2020 project suggests results could be replicable with minor modifications, as much of the unknowns and alternatives have been explored through the previous case studies.

The limitation on thesis size has restricted the reporting of much of the research to the appendix. Case study reporting, the extent of communications in the pilot project and simulation analysis are all contained in the appendices. Beyond that there is a great deal of historical information of formation of the RTCs and their design, which could not be included in this document but will inform future research papers. Much of the content analysis depended on minutes and reports, which can sometimes lose the individual voice, and opinions of the participants in the design process, minutes can often conceal interesting conflicts and interactions that can occur at the meetings.

The issue of market financing of deep energy retrofits has arisen as a barrier to nZEB adoption. Whilst this has been highlighted in this study, there is significant scope to further examine this topic and to develop tools to facilitate deep retrofit investment decision-making. This is a developing subject, where the researcher is contributing to Irish Green Building Council, Sustainable Energy Authority of Ireland and Department of Communications, Climate Action & Environment strategies for nZEB adoption. Draft strategies with innovative concepts like linking Building Energy Ratings (BER) to property tax could help address some of the system barriers to NZEB retrofit.

Low energy building retrofit is a complex challenge, open to a very wide variety of inputs, many explored in this study. This study deliberately set out to explore the breadth of forces that impact nearly and net zero energy building retrofit, to examine the impact of those variables on the socio technical process for retrofit decision making and their potential outcomes. As Fryberg (2004)[dclxxvi] had argued case studies can often suffer from too much depth and not enough breath to inform emerging trends and hypotheses. A broad study was needed to address the multi-factorial inputs in low energy retrofit. This is a systems design approach where the impact of potential modifications to the socio technical processes can be fully understood and more accurately anticipated. As such there are aspects of the study where there is the potential for deeper analysis of specific issues; issues like the impact of building performance tools in architectural practice on post occupancy performance in Ireland could be explored in greater detail. The comparisons between the Loughborough University and the RTCs designs are touched on here but there is now a significant body of research that could contribute to new knowledge outside the limits of this study.

8.4 Conclusion

NZEB retrofit is technically possible, but the research has highlighted a number of barriers to the market adoption of nZEB. These are current problems in Ireland, given the impact of the recession on energy conservation policy. As the government comes to grips with policy gaps, it has finally realised that action is required to revise the policy for the national renovation strategy Ireland due to be submitted the EU in April 2017 (Department of Communications Energy and natural Resources, 2014)[dclxxvii]. This research is being used to inform high-level workshops on large-scale deep renovation that will contribute to forming this revised policy.

Motivating the market to a greater level of nZEB adoption will need a significant increase in policy intensity. This is likely to include grant/tax incentives (carrots), regulations (sticks), financing mechanisms to enable deep retrofit and education of both building owners and design practitioners. "As there is a risk that the majority will only meet the bare minimum requirements, high standards are needed" (IGBC 2016)[dclxxviii]. This research identifies the key barriers, establishes potential technical solutions, offers new models for the socio-technical retrofit process, and identifies the shortcomings in financially modelling for building retrofit investment. It is now clear that simplified user centred investment analysis tools together with a greater availability of financing could help set better client goals at the outset of the process. This goal setting together with adequate retrofit budgets are critical to design process options and decision-making. Augmenting the design process should not be seen as a risk of greater demands on Architectural practice but an opportunity to expand fee related services. In the short term nZEB specialists may be needed to fill this gap in experience, knowledge and understanding until practice can come up to speed. Of course without improved policy actions, this is unlikely to happen.

The next and final chapter will conclude with the specific findings from this research, lists the dissemination of the research to date and outlines future opportunities to develop the research area.

CHAPTER 9

CONCLUSION

Chapter 9: Conclusions

9.1 Introduction

Ireland's building energy conservation policies may contribute to €300m in fines (pa) from the EU for missing its 2020 Green House Gas (GHG) emission abatement targets. Deep retrofit is a complex issue, with multiple factors influencing strategic investment goal setting and multiple barriers impacting the technical design challenge of achieving a measured Net Zero Energy Building (NZEB) performance. The research reported in this thesis draws heavily on the involvement in a non-dwelling NZEB pilot project in Ireland, which successfully achieved the aspirations of the EU Energy Performance in Buildings Directive (2010).

By its specific nature Deep Retrofit is a complex technical challenge from a design process standpoint. The design process is subservient to client or investor goals, which can delimit the options, open to the design team. There are wide ranges of factors that influence goal setting, mapped out in figure 9.1, from the level of retrofit regulations, incentives, the availability and cost of credit and the investment analysis models that inform decision-making. Political priorities towards building energy conservation have been governed by external factors such as world energy prices or internal domestic factors. The barriers and knowledge gaps to deep retrofit identified by Golove (1996) and Steinmüller (2008) related to both systemic and technical challenges. Case Study and content analysis of pilot projects and precedent retrofits in Ireland broaden the scope and understanding of these barriers at both systemic and technical levels, at pre-design, design and post occupancy stages (Fig 9.2 & Fig 9.3).

Findings from case study analysis and pilot project retrofits in Ireland reported in this thesis, have established that it is technically possible to achieve a measured 74% reduction in building energy demand, supplemented with an installed photovoltaic array delivering 26% site renewable energy, to achieve an Net Zero Energy Building (NZEB) retrofit performance, through an augmentation to the existing design process. Whilst barriers exist to a typical design process achieving this technical challenge, these are not insurmountable, where there is the market demand to support the appropriate professional services required. The design process is subservient to investor goal setting because it effectively delimits design stage decision-making. This goal setting is open to the systemic forces (Fig 9.1), which influence market behaviour and market demand. The greater challenge to the market adoption of *Deep Retrofit* in Ireland may be the various systemic barriers/external factors that influence performance goals and energy conservation options.

In discussing the existing retrofit investment models in Chapter 5, it was found that they are almost exclusively based on simple payback from operational energy savings, which bias goal setting toward light retrofit strategies, and away from more capital-intensive deep retrofit strategies. Existing retrofit finance models and ESCOs do not recognise the added benefits of capital appreciation, improved interior environmental conditions, extended economic and physical lifespan to the building and its occupants.

Low standards of retrofit regulations, deficient financial incentives, a lack of access to credit, falling energy prices and simple payback models have all coalesced to undermine *Deep Retrofit* demand in Ireland since 2010. As the poorest performance 1960s and 1970s commercial buildings arrive at their renovation cycles, policy instruments and finance models are poorly placed to incentivise deep retrofit. This low policy intensity scenario towards retrofit in Ireland represents a missed opportunity for GHG abatement and improved construction activity.

9.2 Technical challenges

As detailed in the pilot project and case study (CIT Phase 1 & 2) in chapter 7, the provision of a retrofit exemplar that significantly improved environmental performance together with a 74% saving in energy consumption and extended building lifespan failed to shift investor attitudes towards retrofit. The subsequent retrofit budget was cut from 80% to 20% of new build with no regard for environmental or energy performance consequences. This is not an example of ignorance or belligerence but a true reflection of market forces where without a change to the systemic forces, no voluntary change can be expected in goal setting for the design process. In the absence of high energy and environmental performance standards, funding constraints and client goal setting can become cost centric, undervaluing or unconcerned with environmental performance consequences.

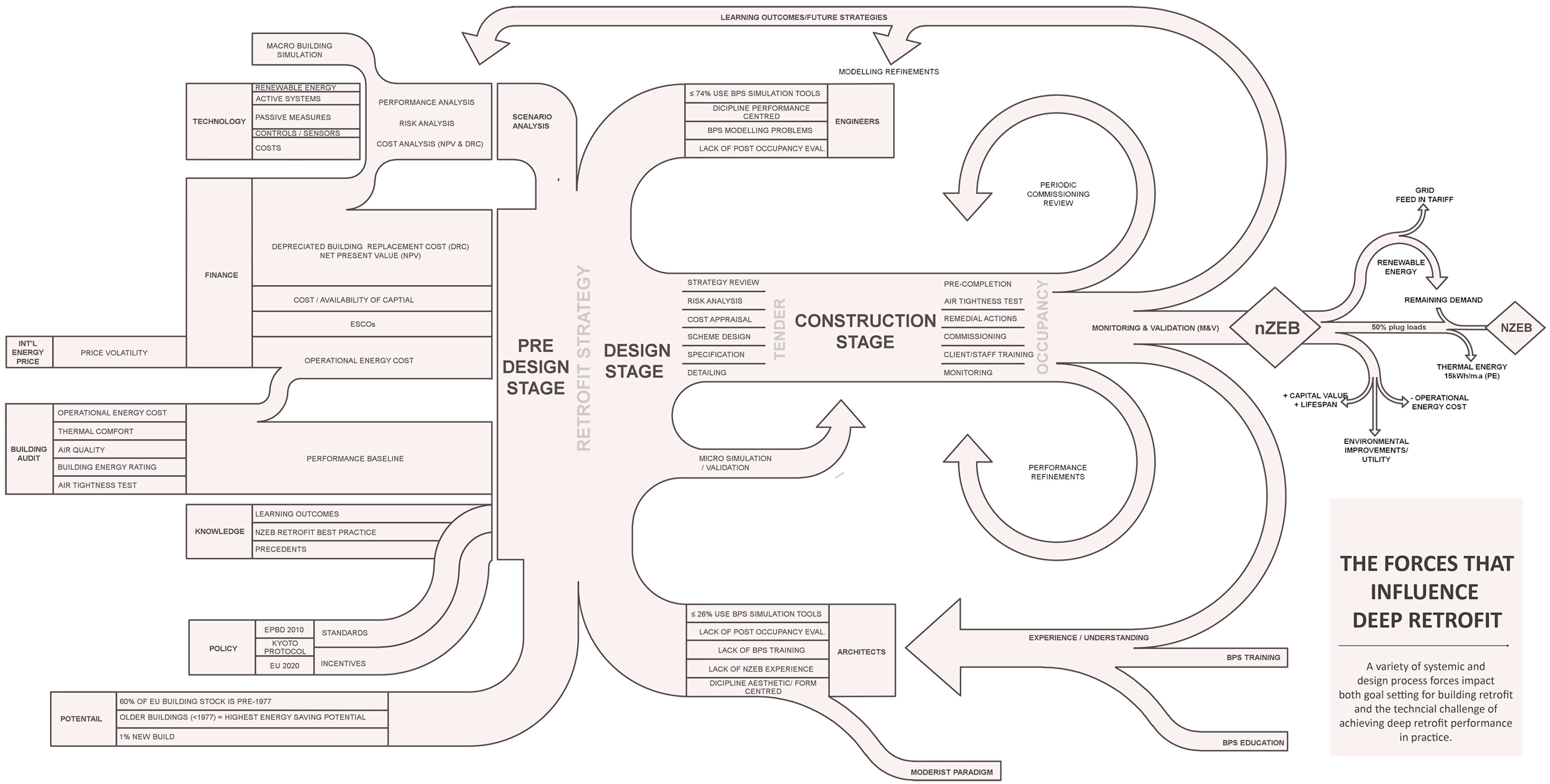

Figure 9.1: The Forces that influence Deep Retrofit (Ó'Riain 2016)

Whilst the pilot project (Zero2020) had failed to shift client demand for *Deep Retrofit*, it was important in a research and practice context. The technical challenge of achieving a ***nearly*** *or* ***Net*** *Zero Energy Building Performance* (**n**ZEB & **N**ZEB) through retrofit had never been established in an Irish economic, legislative and climate context up to 2014. One has to remember that the Energy in Buildings Performance Directive was only recast in 2010 with the definitions of *nearly Zero Energy Building Performance* and cost optimal nZEB still in flux, during the inception of the project. The pilot project established for the first time project costs, potential nZEB performances and practice barriers in an Irish context to NZEB retrofit.

The pilot project (Phase 1) adopted and tested the proposed Socio Technical Process for Deep Retrofit (Figure 9.3) that had been developed to address the barriers to Deep Retrofit in Ireland (Figure 9.2). Building on the success of scenario analysis applications, in shifting/improving goal setting, in the case study retrofits (Ch. 6), the proposed *'Deep Retrofit Process'* extended a pre design stage for strategic goal setting and a post occupancy stage for measurement and validation. Although pilot project (Phase 1) demonstrated a measured nZEB performance a number of issues arose that would result in the amendment of the *'Deep Retrofit Process'*.

Technical issues arose which included the lack of scenario cost analysis, which may have extended the number of design iterations during the design process, in turn limiting the time for simulated performance validation and resulted in design process conflicts. Although the consultant engineer used building performance simulation (BPS) tools to validate the macro building retrofit strategy, the architect did not adopt any BPS tools to validate design detailing or perform risk analysis associated with the super-insulated fabric solution. The lack of knowledge of the potential risk of trapping fabric absorbed moisture posed a very specific risk to validity of the final design. The abridged nature of the commissioning process and complete absence of post occupancy analysis by the design team highlights the lack of performance-oriented validation in existing practice. The project validated the importance of the proposed *'Deep Retrofit Process'* (Fig 9.2) and the subsequent owner-led retrofit demonstrated the subservient nature of the design process to client goal setting.

The subsequent owner driven retrofit demonstrated the impact of commercial drive (Lawson 1980) on client goal setting and the resultant impact on design stage decision-making. Despite the existence of an immediate typologically specific, proven exemplar, market conditions would allow the investors to value engineer many of the inter-dependent aspects of the exemplar design solution out of the scheme for budget reasons. This emphasises the importance of higher policy intensity for retrofit and improved technical design processes to address the wider market adoption of deep retrofit in Ireland.

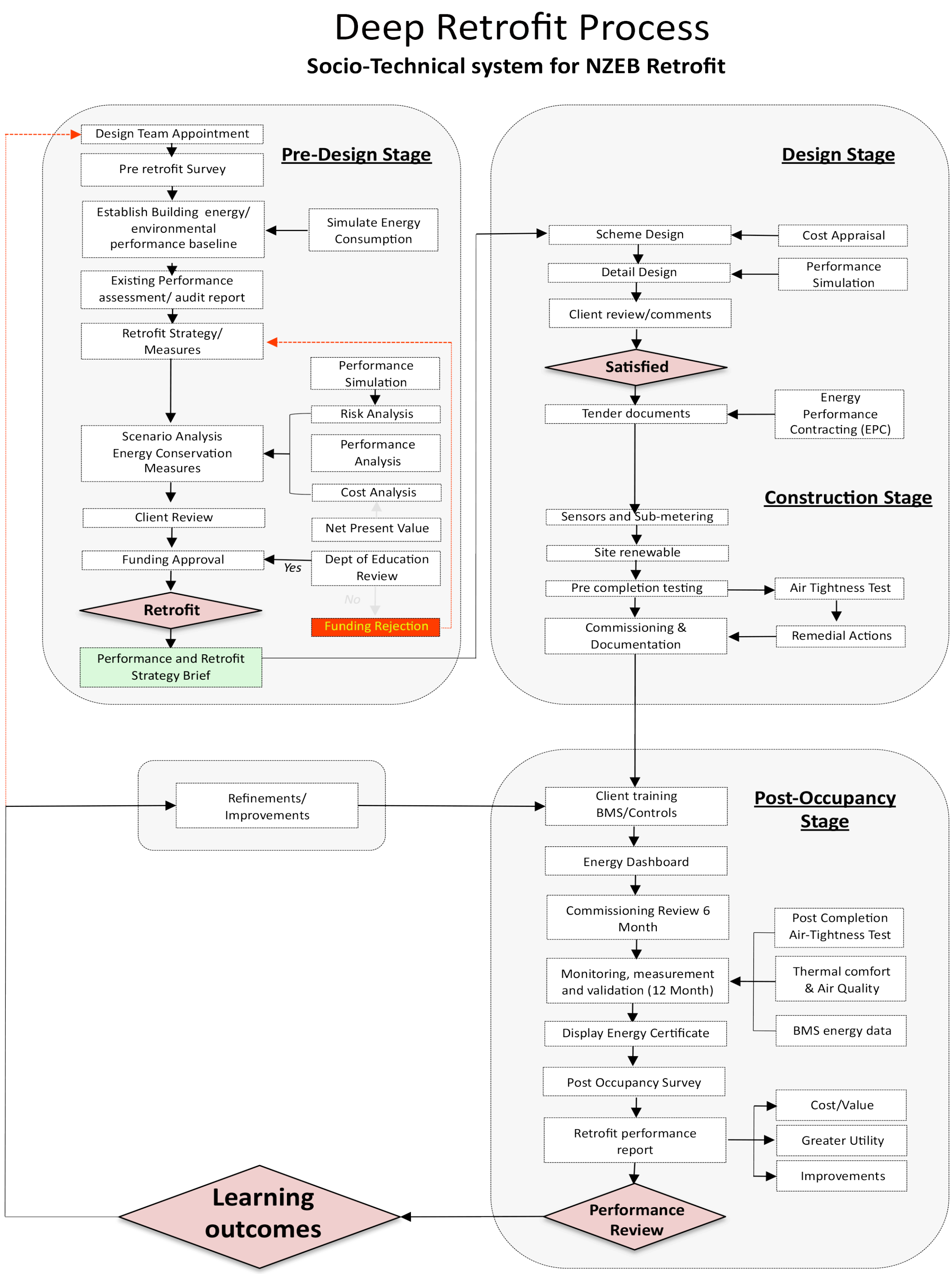

Figure 9.2: Deep Retrofit Process (Ó'Riain 2016)

Without adequate budgets, the selection of appropriate energy conservation measures is limited. The design process itself is constrained by budget and time. Time was one of the main reasons Irish Architects reported for the lack of training in, or adoption of building performance simulation tools (Graph 5.3). The narrow demarcation of the existing design process prevents it from having significant impact on client goal setting for deep retrofit, and the lack of engagement with post occupancy evaluation minimises learning outcomes from case to case. To validate design stage performance, architecture as professional services, would need to charge for the additional deliverables and time demand associated with the proposed *Deep Retrofit Process* (Fig 9.2). Extending the *Deep Retrofit Process* (Fig 9.2), the additional deliverables at pre-design and post occupancy stages could be seen as a opportunity to extend the income of the architect, thus increasing the market demand and desire for BPS training. In the meantime, there is a shortage of nZEB experience and BPS skills within architectural practice in Ireland to address the challenges of deep retrofit partially because of the lack of experience and historical demand. In the current scenario there is an opportunity to augment the existing design team with NZEB specialists, who, in the short term at least, can augment the *Deep Retrofit Process* (Fig 9.2).

The case studies and pilot project analyses in Chapter 6 & 7 highlight the importance of systemic change to framing investor goal setting and the limited impact of the exemplar in changing market behaviour. Market forces need regulation, or the externalities of climate change will never be captured at the final point of consumption.

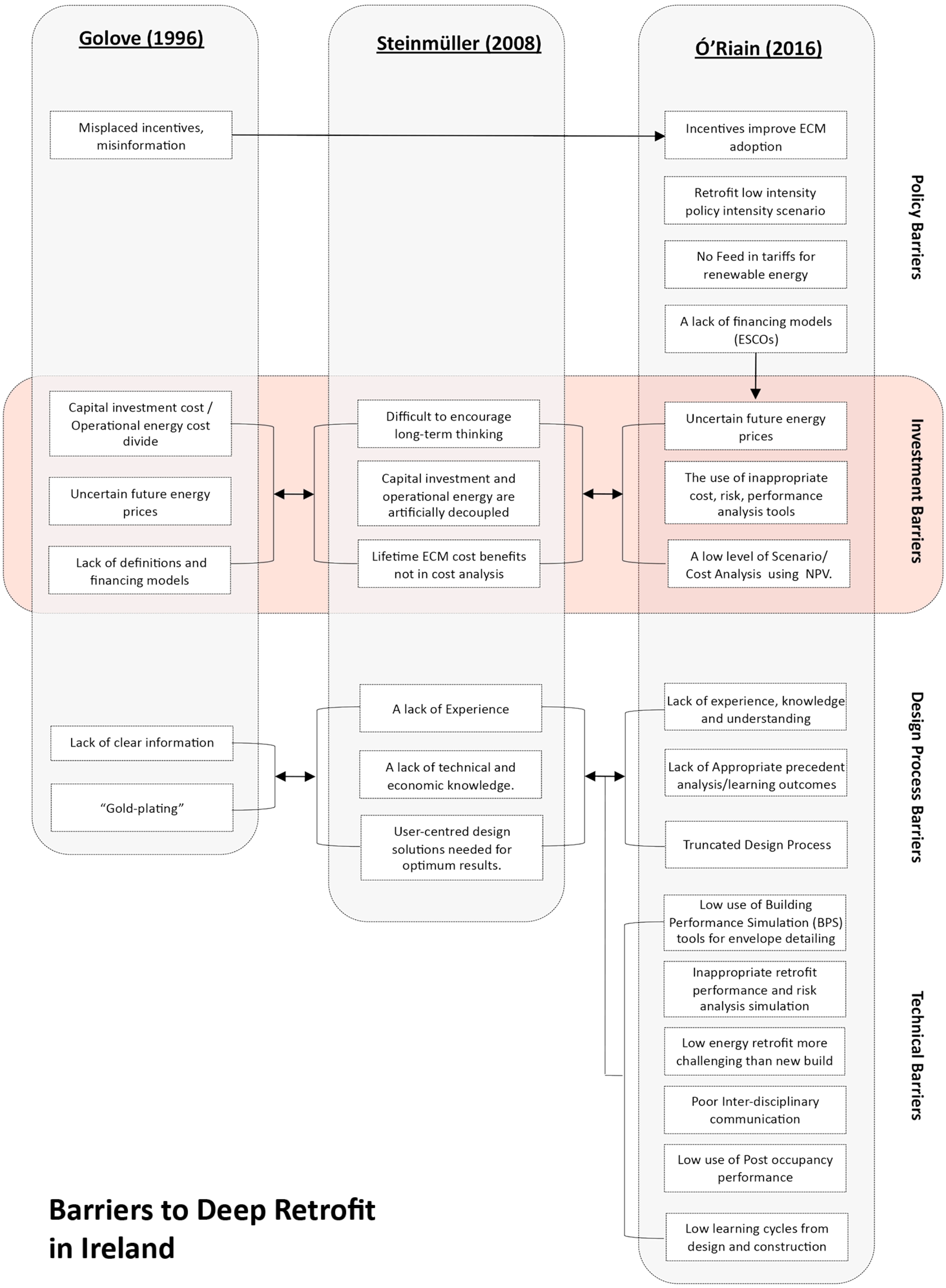

Figure 9.3: Barriers to Deep Retrofit in Ireland (Ó'Riain 2016)

Deep Retrofit Barriers
Socio Technical Process

Pre-Design Stage Barriers

Pre-Design Stage Barriers

- Low intensity Retrofit regulations disincentive deep retrofit client goals.
- A poor level of access to capital finance and finance models (ESCOs) undermine long term investment.
- The use of simple payback methods for retrofit based on operational cost savings undervalues the benefits of added capital value, extended lifespan and environmental improvements, thus biasing decision making toward shallow retrofit strategies.
- A falling level of incentives and the lack of tax breaks for longer term for deep retrofit undermine investment models.
- The lack of scenario analysis by clients and design teams undermine informed strategic decision-making for deep retrofit, extending the design process.

Design Stage Barriers

Design Stage Barriers

- There is a low level of Building Performance Simulation (BPS) analysis for architectural detailing.
- A poor level of appropriate precedent research was carried out at case study buildings.
- The lack of BPS use for risk analysis for thermal bridging and interstitial condensation.
- The lack of post occupancy analysis leading to repeating specification problems (delaminating render, discoloration of render, thermal bridges, mould growth).

Post Occupancy Stage Barriers

Post Occupancy Stage Barriers

- There is a lack of performance validation and post occupancy analysis by design teams and clients.
- A lack of sub metering is a barrier to accurate energy auditing.
- A lack of staged commissioning can impact building energy performance.
- Increased post occupancy plug loads increased electrical energy in the overall energy demand mix.
- Increased utility of the building can often lead to higher energy demand.

Figure 9.4: Barriers to Deep Retrofit in the socio technical process (Ó'Riain 2016)

9.3 Systemic challenges

As discussed in Chapter 5 and illustrated in Figure 9.1, the technical challenge of achieving Deep retrofit goals of Nearly and Net Zero Energy building performance is influenced by a wide variety of factors. Although the proposed Deep Retrofit Process goes some way to addressing the factors internal to the design process, the Phase 2 case study in Chapter 7, demonstrated the low policy intensity scenario that exists in Ireland for building retrofit, allowing investors to rationalise projects to very low cost levels, in spite of the negative performance consequences.

Building on the gaps in knowledge and barriers to low energy retrofit by Golove and Steinmüller, an examination of existing literature, content and comparative analysis of case studies, a pilot project and a subsequent control retrofit, inform a series of specific barriers to deep retrofit in an Irish economic, legislative and climate context (fig 9.3 & 9.4). This research supports the findings of Golove (1996) and Steinmüller (2008), extending and broadening their findings to an Irish economic, legislative and climate context (fig 9.3 & 9.4). Discussion of these barriers is covered in Chapter 8.

Government inaction and market forces cause many of the systemic barriers. Continued low policy intensity regarding building energy retrofit in Ireland has failed to shift market behaviour. Client retrofit decision-making, without the control of regulations, has been observed to undervalue the potential for deep retrofit to address failing building envelopes and the resultant “deterioration” of interior environmental conditions. Buildings depreciate over their lifespan, as building elements approach, and pass the end of their physical or mechanical lifespan. The short term nature of retrofit incentives, the lack of a feed-in tariff, the cost and availability of capital and the longer payback periods all bias investment towards light retrofit and away from deep retrofit solutions. The use of simple investment payback methods can bias design stage decision-making toward light retrofit solutions and away from deep retrofit solutions.

Regulations have a key role in setting a baseline of expected performance and controlling the commercial drive of investors. With no improvements in building energy retrofit regulation since the first Energy Performance Directive in 2002; there is significant scope to improve these standards. The revision of these standards, proposed for 2017 will be informed directly by the Irish Cost Optimal Calculations (2013 & 2015). These calculations fail to acknowledge the age of the building, remaining building lifespan or the environmental consequences of proposed retrofit packages.

Cost optimal calculations, which were discussed at length in Chapter 5 and in the published paper in Architectural Science Review, retain a focus on the payback of an energy conservation measure through operational cost savings.

This common and frequent focus on elemental or retrofit measure payback biases towards light retrofit and against deep retrofit strategies, because of shorter operational cost saving payback periods associated with lighting upgrades, the installation of thermostatic control valves and the replacement of boilers with high efficiency condensing boilers. The perception of deep retrofit on the other hand suffers from higher up front capital costs, variable interest rates, volatile energy costs, the lack of energy auditing, and the lack of post occupancy measurement and validation (Ch. 5.10).

Building owners are failing to recognise the requirement for a significant capital reinvestment needed to the arrest deteriorating fabric condition and extend the building for a second lifespan, equivalent to that of a new build, delivering greater asset value, building utility and comfort. Although 'Net Present Value' is widely used in the investment industry, case studies would indicate that it does not appear to be used in investment analysis for building retrofits or in cost optimal calculations (Ch. 5.9). The lack of high intensity retrofit regulations allows the investor to value engineer solutions down to low levels of investment without any mandatory performance, risk analysis or performance impact assessment for retrofit. Indeed in the cost optimal calculations report by AECOM 2015, commissioned by the government, they found that existing retrofit standards in Ireland appeared not to be enforceable (Ch. 5.3)[28]. In appearing to contradict the learning outcomes of 40 years of research and best practice in low energy design, Irish cost optimal calculations recommend that nZEB performance levels are achievable without fabric retrofit.

9.4 Market Barriers to *Deep Retrofit* in Ireland

Although the Energy Performance Directive was recast in 2010 with a view to increasing the adoption of low energy nZEB buildings, Ireland still has only one measured non-dwelling nZEB retrofit, the pilot project, Zero2020. The recession in Ireland had a major part to play in Government attitudes towards our environmental commitments. The Taoiseach (Prime Minister) accepted (in 2016) that Ireland would miss its 2020 emission targets because of policy inaction (Ch. 5.10). Where Ireland has been successful in motivating market

[28] The application of building regulations for energy conservation to existing buildings can be very subjective as…. "the adherence to guidance, including codes, standards or technical specifications intended for application to new work may be unduly restrictive or impracticable" in existing buildings (Environ 2008)

adoption of better energy performance in new dwellings through more intensive energy conservation regulations (2011), the market adoption of nZEB performance buildings has been a market failure to date.

As Ireland emerges from a severe recession, economic and construction activity has begun to rise rapidly along with emissions indicating Ireland is 40%-75% off its committed GHG emission targets for 2020 (Ch. 5.6), and potentially faces fines of €50m-€300m per annum from 2020. The Department of Communications, Climate Change and the Environment (DCCAE) have accepted the need to dramatically increase the rate of 'deep retrofit' as an abatement strategy, which may have "a high upfront costs, but can lead to significant energy savings. Examples include external insulation, installation of heat pumps, and installation of triple glazed windows" (DCCAE 2016)[dclxxix]. The DCCAE also noted the need to introduce progressively more stringent building regulations, which falls outside the Department's remit. The Department of Housing Planning, Community and Local Government (DHPCLG) are in control of the proposed revision to commercial building regulations timetabled for 2017. These will be informed by the cost optimal calculations commissioned by the DHPCLG in 2013 & 2015, which propose revisions to the existing, very poor level of building energy retrofit regulations. The cost optimal calculations findings do not include *Deep Retrofit* measures, historically associated with NZEB retrofit (like external insulation and triple glazed windows) as outlined by the DCCAE in its 2015 report.

The greatest threat to higher intensity building retrofit regulations in Ireland is the cost optimal calculations as they are set out in their current form. Chapter 5 highlighted the impact of the calculations, using the energy consumption of a "universally unrepresentative" set of reference buildings (primary schools), the skewed results of Irish cost optimal calculations could shift best practice toward active energy conservation measures, ignoring continued fabric dilapidation, diminishing environmental conditions, delayed maintenance, building lifespan and capital value. The recommendations of the final report on cost optimal nZEB in Ireland found, unlike the UK, that fabric retrofit was not needed to achieve nZEB performance in Ireland. The 'cost optimal calculations' may undermine Government targets for 'Deep Retrofit'.

No new regulations have been introduced to improve minimum standards; ESCOs have almost totally left the market; incentives have fallen; financing initiatives have failed and there is only one solitary measured non-dwelling NZEB retrofit in Ireland (Zero2020). The proposed draft revision of building energy regulations (2017) has been delayed. However in a private meeting with Sean Armstrong (Armstrong 2015)[dclxxx], the Head of Standards at the Department of Housing, he welcomed the paper 'Cost-Optimal Passive versus Active NZEB: How cost-optimal calculations for retrofit may change NZEB best practice in Ireland, (Ó'Riain and Harrison 2016)[dclxxxi], accepting some of the shortcomings to the 'Cost Optimal Calculations'.

In 2016 the Irish Green Building Council were commissioned to hold workshops on nZEB commercial retrofit, to develop a position paper which offers 10 steps to better nZEB market adoption. This position paper will inform the Department of Communications, Climate Change and the Environment (DCCAE) V2.0 National Renovation Strategy which Ireland must deliver to the EU by April 2017 (IGBC 2016)[dclxxxii].

Whilst the *Deep Retrofit Process (Fig 9.2),* which builds on a great deal of precedent publications, offers guidance in expanding the stages, deliverables and competencies of the design process, it will not achieve the goal of Deep Retrofit without systemic changes in regulations, access to credit, incentives, taxes and knowledge.

As Fraunhofer and Ecofys (2010) had stipulated (Ch. 5.10) Ireland needs to develop a high intensity policy scenario for retrofit in Ireland to increase the adoption of Deep Retrofit performances like Nearly and Net Zero Energy. The EPBD requires Ireland to transpose EU Directives and achieve these performances on the ground. However, to date, the market adoption of this policy has been a failure in Ireland. Retrofit goal setting has been shown as key to driving design team decision-making. Goal setting for *Deep Retrofit* in Ireland has been undermined by a lack of incentives or grants, the lack of high intensity building energy retrofit standards, the limited availability of credit, falling energy prices, the lack of energy auditing, the lack of feed in tariffs and a focus on simple payback methods, all making the business case for deep retrofit a very difficult investment challenge.

Higher education modules and practice based continued profession development (CPD) courses would help inform undergraduates and design team professionals on the process of designing for NZEB retrofits and techniques for using BPS tools.

To address the issue of investor goal setting, future research should develop an accessible financial decision-making tool, which would allow building owners and investors analyse energy conservation measures, building lifespan, capital asset value, future operational cost savings, environmental performance, future savings discount rates and inflation. Such a tool would offer costs, benefits and outline strategies for deep retrofit to investors at the pre-design stage.

9.5 Significance of research

Deep Retrofit is a very difficult challenge with multiple inputs (Fig 9.4), illustrated by the breath of the research. As energy, an international commodity, is the central issue of deep retrofit, the subject is therefore open to the vagaries of the market and geo politics. Government policy can encourage or discourage investment in deep retrofit. Shorter lifespan retrofits, which can carry less risk, can be judged more attractive than deep retrofit options with less quantifiable benefits. Designing technical solutions like Zero2020 might have appeared like the correct solution at the outset of the research, but in truth the systemic challenge of the wider market adoption of Deep Retrofit remains the ‘wicked problem’ that prevents a more effective GHG emission reduction in the built environment. Zero 2020 did become the first measured Net Zero Energy Building Retrofit in Ireland. It has been recognised in national awards, international research papers, published in industry magazines, provided outreach to over 3500 researchers on the website and has become an exemplar training tool for practice (Table 9.1).

Year	**Practice based Publications, Websites and Awards**
2016	http://www.zero2020energy.com
2015	Prejudice Power and Politics in Education: The Regional Technical Colleges (Ó'Riain 2015)
2015	Low Energy Retrofit and Renovation of a Precast Concrete Building in Ireland Exploring site NZEB energy retrofit in Precast Grid Optimized Low Rise '60s Buildings (Ó'Riain, Harrison and McCartney 2015)[dclxxxiii]
2014	A Zero2020 conference paper was recognised with the best student paper, at the Architecture and Civil Engineering Conference in Singapore, 2014.
2013	The Zero2020 project was recognised for the Irish Design Sustainability Award 2012 –Institute of Designers in Ireland
2016	The Zero2020 Project was selected for a National Exhibition in the Global Irish Design Challenge in June 2016.

Table 9.1 Practice based Publications, Websites and Awards

Whilst this PhD research project may be unconventional in the breadth of its scope it was necessary in order to understand the multiple factors that influence the entire process. As a trained designer, the author has followed a systems design approach, attempting to understand the consequences of actions on the entire system, like a sequence of levers and pulleys, to better inform potential solutions. For solutions to be developed, and to induce their combined potential impact, it was important to identify the barriers to Deep Retrofit that are specific to Ireland's legislative, economic and climate context (Figure 9.3) and to address these barriers to the design process (Figure 9.4). The impacts of the barriers, which have been discussed above, illustrate the dominant influence of goal setting on design stage decision-making. Whilst there are communication, deliverables, demarcation, and skills problems in the design process, these can be addressed through a greater demand for *Deep Retrofit*, driving training, additional fees for additional services and implementing the adoption of the expansion of the *Deep Retrofit Socio Technical Process* (Figure 9.2).

Figure 9.1 maps the complexity of this process, illustrating the interactive nature of the inputs, and the potential sensitive inter-dependence of many parts of the process on performance outcomes. The theory of the *Butterfly Effect* suggests that small changes in the initial conditions of a complex system can dramatically influence results. Whilst changes to building standards at the outset of the new building process was shown to have a dramatic effect on the energy performance of dwellings after 2011, the multiple dependencies of Deep Retrofit, on capital investment and credit for example, may require a wider set of changes to result in the market adoption of *Deep Retrofit* in Ireland.

The results of research thesis is contributing to the political policy dialogue in Ireland, which it is directly informing the revision of Building Energy Conservation Standards (Part L 2017) and strategies for the wider market adoption of Deep Retrofit in Ireland. The findings have informed multiple conferences, influencing stakeholders and refocusing the topic on system barriers (Table 9.2).

	Conference presentations, training, outreach
2016	German-Irish Passive House and Energy Efficient Buildings Conference April 2016
2015	See the Light Conference, Dublin. 13th November 2015[dclxxxiv]
2015	NZEB Open Doors Ireland, Cork. 14th November 2015[dclxxxv]
2015	Open House Cork, 10-12th April 2015[dclxxxvi]
2014	NZEB Open Doors Ireland, Cork. 8h November 2014[dclxxxvii]
2014	Construction Industry Federation, Cork. Zero energy Day 19th June 2014[dclxxxviii]
2014	Architecture and Civil Engineering Conference, Singapore, 25-26th April, 2014[dclxxxix]
2013	2nd AIARG Conference, Limerick. 25th January, 2013[dcxc]
2013	Retrofit Conference, Dublin. March 20, 2013[dcxci]
2012	See the Light Conference, Cork. 7th September, 2012[dcxcii]

Table 9.2 Conference presentations, training, outreach

The research is topical and timely, providing a systemic overview of the forces that influence building energy retrofit in Ireland today. Whilst it may have started out attempting to inform architectural practice, the major influence may be at a policy level, which can hopefully enable architects to adopt ever more efficient energy design strategies. The seminal peer reviewed publications from the research are contributing to the policy dialogue for Deep Retrofit (Table 9.3).

Year	**Peer Reviewed Journal Articles**
2016	Cost-Optimal Passive versus Active NZEB: How cost-optimal calculations for retrofit may change NZEB best practice in Ireland, (Ó'Riain and Harrison 2016)[dcxciii]
2016	The forces that shaped the Irish Regional Technical College buildings, (Ó'Riain 2016) [dcxciv]
2015	Low Energy Retrofit and Renovation of a Precast Concrete Building in Ireland Exploring site NZEB energy retrofit in Precast Grid Optimized Low Rise '60s Buildings (Ó'Riain, Harrison and McCartney 2015)[dcxcv]
	Peer Reviewed Conference Papers
2014	Zero2020 the low energy retrofit and renovation of a precast concrete building (Ó'Riain, Harrison and McCartney 2014)
2013	Design and Performance of an external building envelope retrofit solution for grid optimised concrete structure: A case study (O'Sullivan, Delaney, Ó'Riain, Clancy, O'Connell 2013)
2012	A Design Framework for Achieving Net Zero Energy Commercial Buildings. (Hyde et al. 2012)

Table 9.2 Conference presentations, training, outreach

A fundamental guide was created to aid investors, architects, building designers understand the principles of Net Zero Energy Retrofit. From the survey in chapter 5 the researcher found the need to develop the *Fundamentals of Zero Energy Retrofit*[dcxcvi] *(Fig 9.5)*, not as rigorous piece of academic research, but to contribute to general knowledge, as a starting point for practice. It includes an illustrated introduction to the topic summarising of the basic elements that inform low energy building energy retrofit. This has been published and is available on Amazon.com[29].

[29] *http://www.amazon.com/Fundamentals-Energy-Retrofit-ÓRiain-Correia/dp/1364330660/ref=sr_1_1?s=books&ie=UTF8&qid=1456513384&sr=1-1&keywords=zero+energy+retrofit*

9.6 Recommendations for future research

There is now the basis and scope to develop further research into retrofit financial tools and models for assessing the cost optimality of various energy conservation measures for a variety of non-dwelling applications, together with a buildings net present value, operational energy costs and capital value. This is the basis for an upcoming EU Horizon2020 funding bid.

9.7 A final word

Deep Retrofit is a systemic and technical challenge, where external factors drive investor goal setting, which in turn influences the scope of design stage decision making. The design process, as currently constructed, is abridged, with little potential impact on client goal setting and little interest in validating post occupancy performance. If we are to see Ireland meet its 2020 greenhouse gas emission targets, the government will have to get to grips with the barriers outlined in this research. There is a huge potential for *Deep Retrofit* to play significant role in GHG abatement, with systemic and technical improvements required.

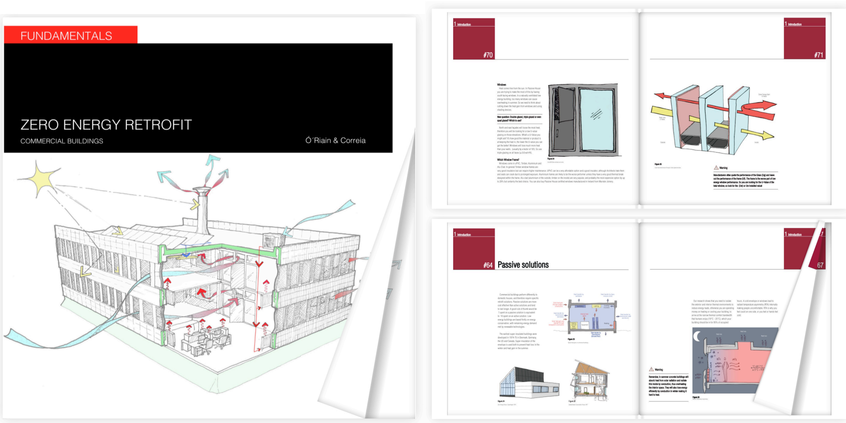

Figure 9.5 Fundamentals Zero Energy Retrofit –Appendix 8 (Ó'Riain and Correia 2016)

CHAPTER 10

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